



ESCUELA TÉCNICA SUPERIOR DE INGENIEROS INDUSTRIALES Y DE TELECOMUNICACIÓN

Titulación :

INGENIERO INDUSTRIAL

Título del proyecto:

NUMERICAL AND EXPERIMENTAL STUDY OF A
PYROSHOCK TEST SET UP FOR SMALL
SPACECRAFT COMPONENTS

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Pamplona, 22 Julio 2010

INDEX

1	INTRODUCTION	3
1.1	GENERAL CONTEXT	3
1.2	OBJECTIVES.....	3
1.3	SUMMARY	4
2	EXPERIMENTAL TESTS	6
2.1	FIRST SETUP	6
2.2	SECOND SETUP	8
3	NUMERICAL SIMULATION	11
3.1	CODES.....	11
3.1.1	AUTODYN	11
3.1.2	ANSYS	12
3.1.3	CONWEP	13
3.2	NUMERICAL SIMULATION WITH AUTODYN	14
3.2.1	FIRST MODELING	14
3.2.2	SECOND MODELING	38
3.2.3	OTHER SIMULATIONS (10G, 30G AND 40G)	48
3.3	NUMERICAL SIMULATION WITH ANSYS.....	60
3.3.1	FIRST MODELING	60
3.3.2	SECOND MODELING	65
3.4	CONCLUSIONS	70
4	CONCLUSIONS	72
5	APPENDIX A: EXPLOSIONS.....	73
5.1	DEFINITION AND CLASSIFICATION	73
5.2	TNT EQUIVALENCE	73
5.3	PHENOMENOLOGY OF AN EXPLOSION	74
5.3.1	GAS EXPLOSION.....	74
5.3.2	THERMAL RADIATION.....	75
5.3.3	FRAGMENTATION.....	76
5.4	REPRESENTATION OF THE SHOCK WAVE	76
5.5	REFLECTION OF A SHOCK WAVE	77
6	APPENDIX B: PYROSHOCK TESTING.....	78
6.1	DEFINITION AND CHARACTERISTICS	78
6.2	PYROSHOCK ENVIRONMENTAL CATEGORIES.....	78

6.3	DEFINITION OF THE BEHAVIOR OF A DYNAMIC SYSTEM	78
7	BIBLIOGRAPHY.....	80
8	INDEX OF FIGURES.....	81
9	INDEX OF TABLES.....	84

1 INTRODUCTION

1.1 GENERAL CONTEXT

Pyroshock is the response of a structure to high frequency (thousands of hertz), high-magnitude stress waves that propagate throughout the structure as a result of an explosive event.

The separation of the booster rockets on the space shuttle or the unlocking of mechanisms among others explosive events are performed by fast cutting devices using explosive charges. The detonation of these cutting devices causes a shock wave characterized by high accelerations and vibrations. It is necessary to study the shock wave generated by an explosion in order to avoid the possible irreparable damages that this wave may cause in the elements.

At first, these high accelerations weren't taken into account due to their short duration, but it has been demonstrated that despite their short duration, they have an important influence on the operation of the electronic elements. Although pyroshock rarely damages structural members (except in the regions close to the place where the explosion takes place), it can cause failures in electronic components that are sensitive to the high-frequency pyroshock energy. Examples of these failures induced by the pyrotechnic shocks are cracks and fractures in crystals, ceramics, epoxies, glass envelopes, solder joints and wire leads, seal failure, migration of contaminating particles, relay and switch chatter and transfer. [1]

To ensure the correct behavior of each and every element, not only are necessary vibrations, temperature or functional tests but also pyroshock tests. In many industries such as the car industry, the aero spatial industry and of course in the military field it is important to carry out these pyroshock tests. Although the elements are the first affected by the pyrotechnic shocks it is important to remember that it is not just about the correct performance of them but also about the safety of the people who use these elements or who can be affected by a bad conduct of them.

To reduce the number of experimental tests that should be done to verify that the accelerations reached by an element are within the specifications, numerical simulations are carried out. Numerical simulations allow us to achieve results without having to design and build the model over and over and they make it possible to change the parameters of study almost instantly.

1.2 OBJECTIVES

In order to know if specific spacecraft equipment and components will withstand the extremely high accelerations and vibrations due to booster disconnection or stage separation using small explosive charges, small scale pyroshock tests have to be carried out before the actual launching of the spacecraft. With these tests, shock and vibration conditions similar to the conditions encountered during an actual launch are created.

In this project pyroshock tests will be simulated in order to compare the simulated accelerations with the experimental ones by means of:

- Time history signal: The time history is usually described in terms of its absolute peak acceleration and its duration.
- SRS (Shock response spectrum): The shock spectrum response is the graphical representation of an arbitrary transient acceleration input in terms of how a Single Degree Of Freedom (SDOF) system responds to that input. It is important to know that any transient waveform can be presented as a SRS, but the relationship is not unique; many different transient waveforms can produce the same SRS. As we only track the peak instantaneous acceleration, the SRS does not contain all the information in the transient waveform from which it was created. For example, the curve SRS due to a high acceleration but short duration shock can be achieved by a low acceleration but long duration shock. Both of them would have the same SRS but the damage caused by each one wouldn't be the same.

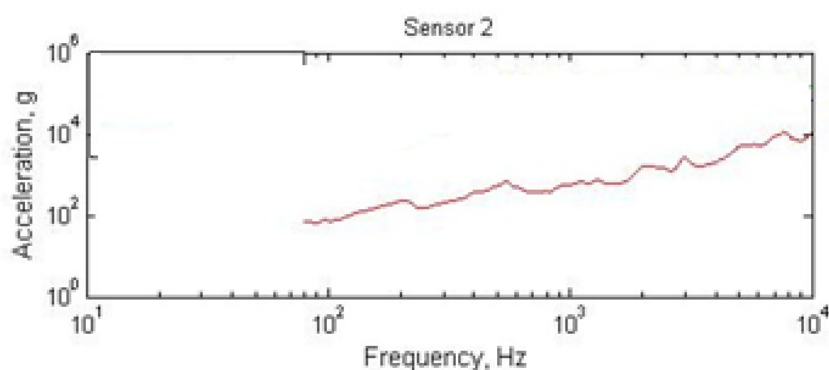


FIGURE 1: EXAMPLE OF SRS

1.3 SUMMARY

This project has four main chapters (introduction, experimental tests, numerical simulation and conclusions) and two appendices where everything related to explosions and pyroshock is explained.

Chapter 1: Introduction

This first chapter shows the context of the project such as the objective pursued: simulate a pyroshock test and compare the numerical results with the experimental ones.

Chapter 2: Experimental tests

This chapter describes the two different setup studied. The first one consists of two plates separated 0.08 m and the detonating cord on the plate below. The second one consists of one plate and a spherical explosive charge. The first setup corresponds to the reproducibility tests that were done during these past years while the second one is a simplification of the first one in order to obtain the whole dynamic behavior of the plate.

The results that are going to be presented in this chapter are the time history signal and the SRS from the experimental tests. The results obtained from the numerical simulations can be compared with the experimental ones in order to achieve the model whose results are closer to reality.

Chapter 3: Numerical simulations

Three different codes are going to be used in this project: AUTODYN, ANSYS and CONWEP. AUTODYN and ANSYS are finite elements software, the main difference is that while AUTODYN is an explicit finite element software, ANSYS is an implicit one. CONWEP is used to calculate the blast loading data (overpressure, impulse and positive phase duration).

Several models for the first and the second setup will be simulated in AUTODYN and ANSYS in order to achieve the correct profile and value for the accelerations.

The first step taken using AUTODYN is the simulation of the detonation of the explosive (Euler-Lagrange solver) and the application of the pressure reached by the explosion on the plate (Lagrange-Boundary conditions solver). It is possible to know the pressure reached by a specific amount of explosive with the use of CONWEP. The modeling for the second setup tries to reach the value of the accelerations by applying the pressure distribution given by CONWEP and different positive phase durations (constant positive phase duration, positive phase duration given by CONWEP or duration calculated through the impulse, given also by CONWEP).

The steps followed in ANSYS are going to be the same as in AUTODYN except for the use of the explosive as it is impossible to implement it in this implicit finite elements software.

Two more important points will be studied in this chapter: the influence of the length of the simulation in the SRS and the relationship between the SRS corresponding to different charges of explosive.

All the results obtained from the different models are shown in order to know which one represents the behavior of the shock plate in a more realistic way.

Chapter 4: Conclusions

This chapter exposes a short summary of what has been done and what should be the continuation of this project in order to achieve numerically the exactly SRS of the experimental results.

2 EXPERIMENTAL TESTS

Experimental tests have to be carried out in order to know the value of the real accelerations the shock plate is suffering. Without these experimental results it wouldn't be possible to know if the numerical results obtained are correct and therefore the model.

2.1 FIRST SETUP

The setup for the first experimental test consists of two plates of steel separated 0.08m. The dimensions of the plates are 1mx1mx0.01m (see figure 2 below).

The plate from above is the one which is going to suffer the accelerations caused by the detonation of the explosive situated on the plate below. The plate above hangs from four springs (in order to avoid possible damages in the configuration) while the plate from below is fixed in the floor through a support.

The explosive used is a detonating cord of 50 cm of length which is equivalent to 50g of TNT and it is fixed in the middle of the plate.

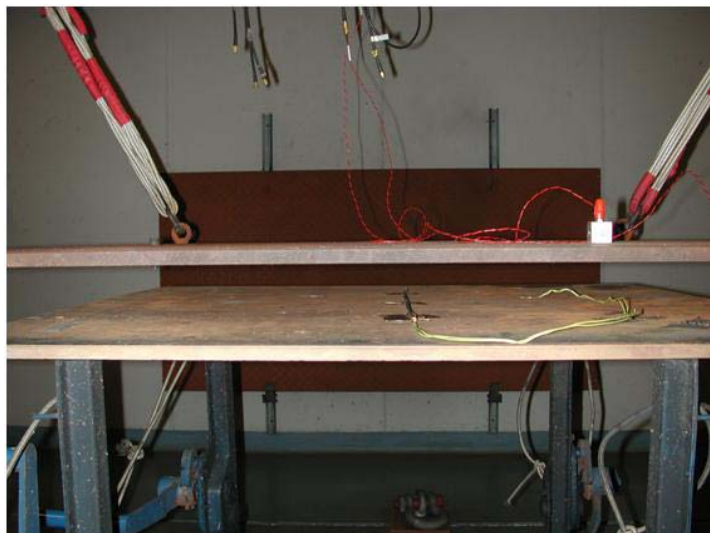


FIGURE 2: FIRST SETUP

In this first setup, two accelerometers are placed on a small plate screwed on the shock plate. The position of these accelerometers corresponds to the positions that have been used in the reproducibility tests done in the past few years. Figure 3 shows the schematic representation of the first set-up.

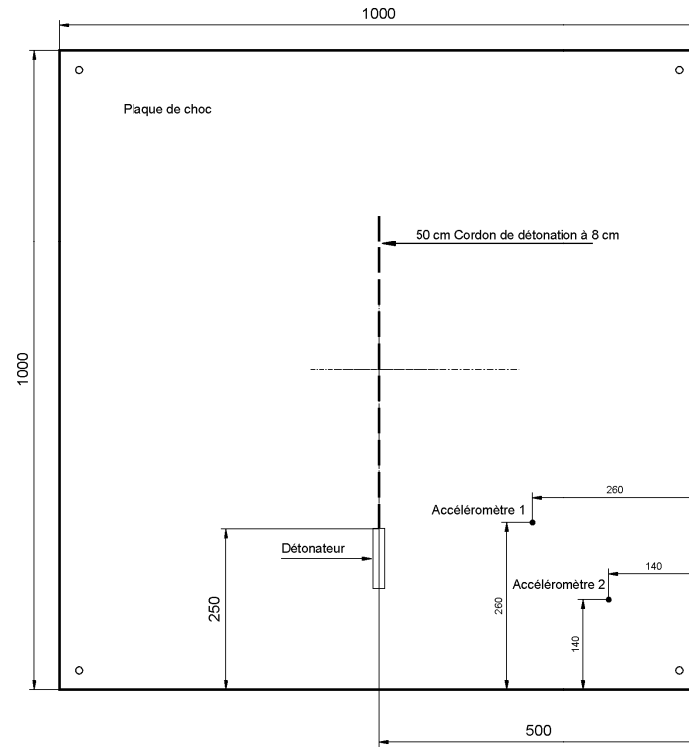


FIGURE 3: CONFIGURATION OF THE FIRST SETUP

The results for the accelerations are the presented in figure 4.

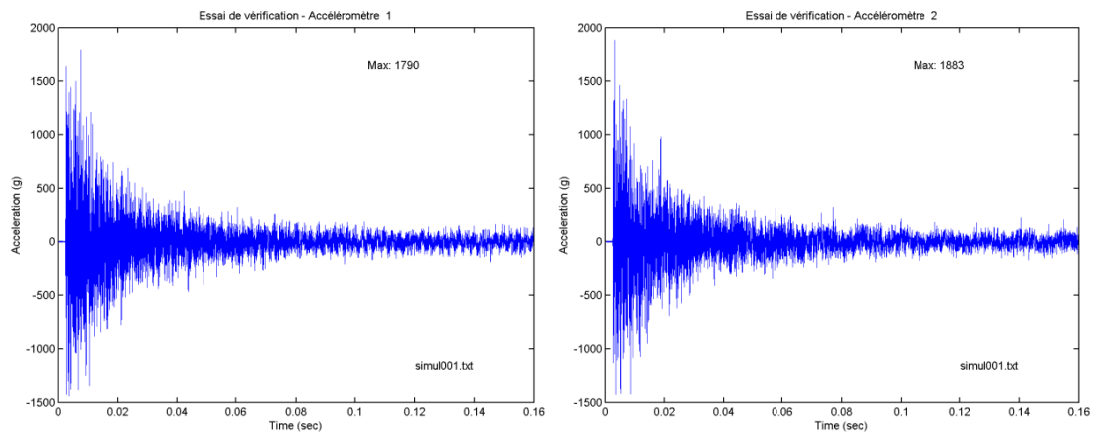


FIGURE 4: ACCELERATIONS FIRST SETUP

The maximum value of the acceleration for the first accelerometer is 17900 m/s^2 . For the second one a value of 18830 m/s^2 is reached.

Figure 5 shows the SRS for the first and second accelerometer.

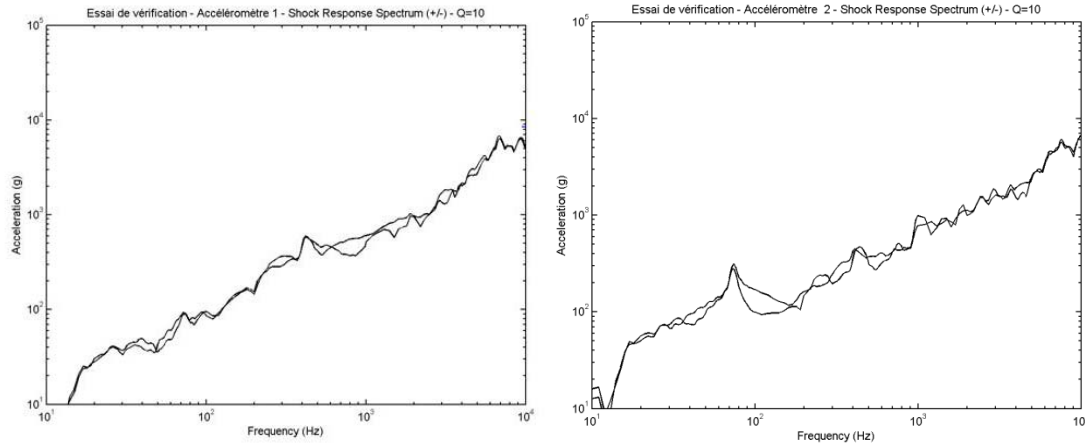


FIGURE 5: SRS FIRST SETUP

2.2 SECOND SETUP

The second modeling differs from the first one on the position and number of accelerometers and on its easier configuration (figure 6). A small plate screwed on the shock plate will not be any longer used. The accelerometers will be placed on the shock plate itself which hangs from four springs, one in each corner of the plate.

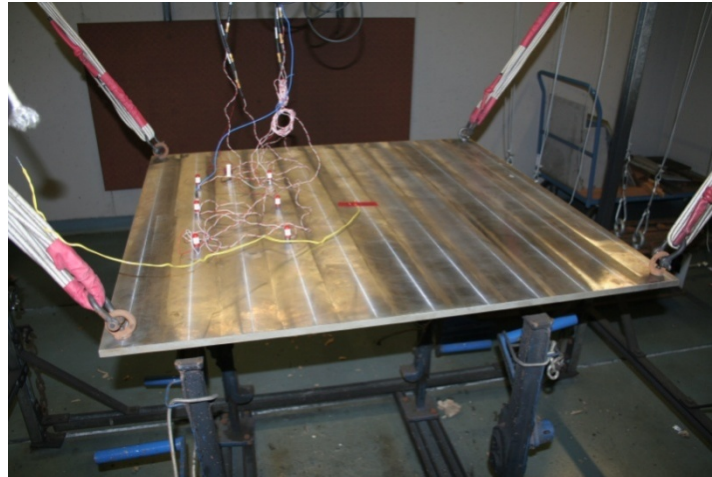


FIGURE 6: SECOND SET UP

The explosive will be no longer a detonating cord but a sphere of 0.02 kg of C4 as shown in figure 7. The explosive is not placed on the plate as it was in the first setup.



FIGURE 7: EXPLOSIVE SECOND SETUP

Nine shock accelerometers were supposed to be placed on the shock plate. Finally only six were placed because the ones just above the explosive could break. These accelerometers were placed on the half of the upper face of the shock plate in order to catch the complete dynamic response of the plate. In this work, the dynamic behavior of the plate is assumed to be symmetric.

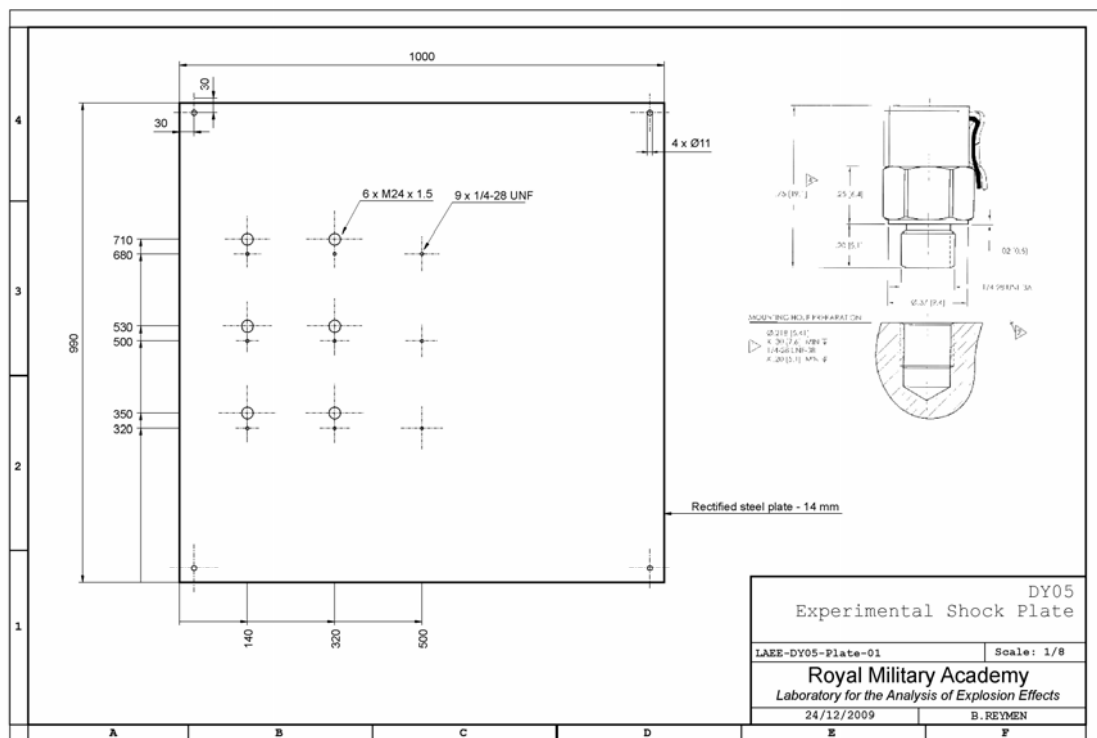


FIGURE 8: CONFIGURATION OF THE SECOND SETUP

Figures 9 and 10 show the experimental accelerations and SRS of the six accelerometers placed on the plate.

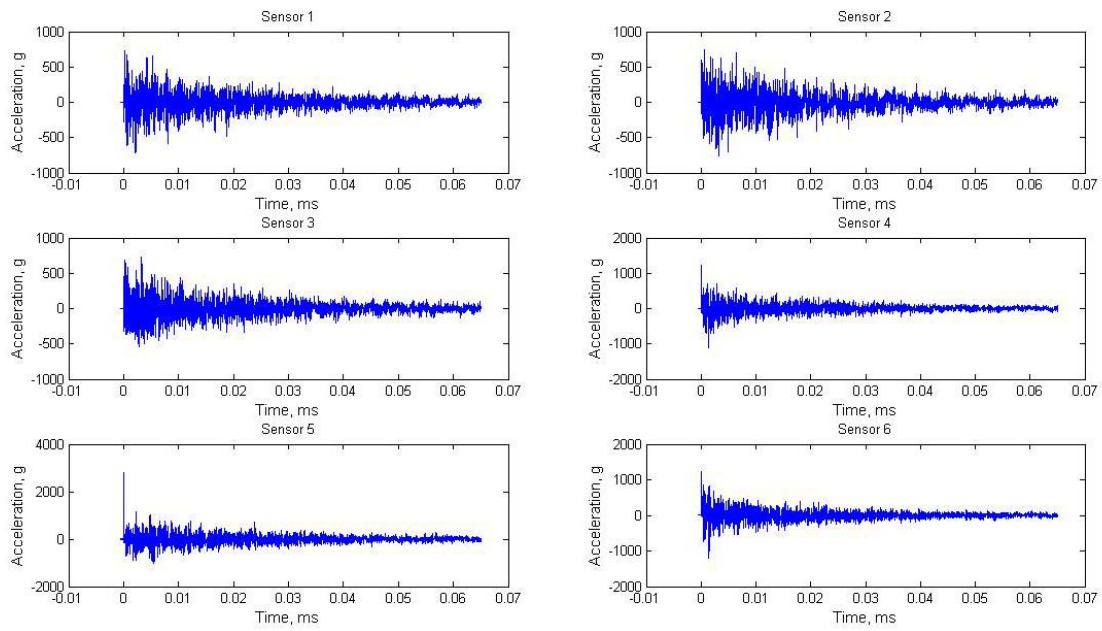


FIGURE 9: ACCELERATIONS SECOND SETUP

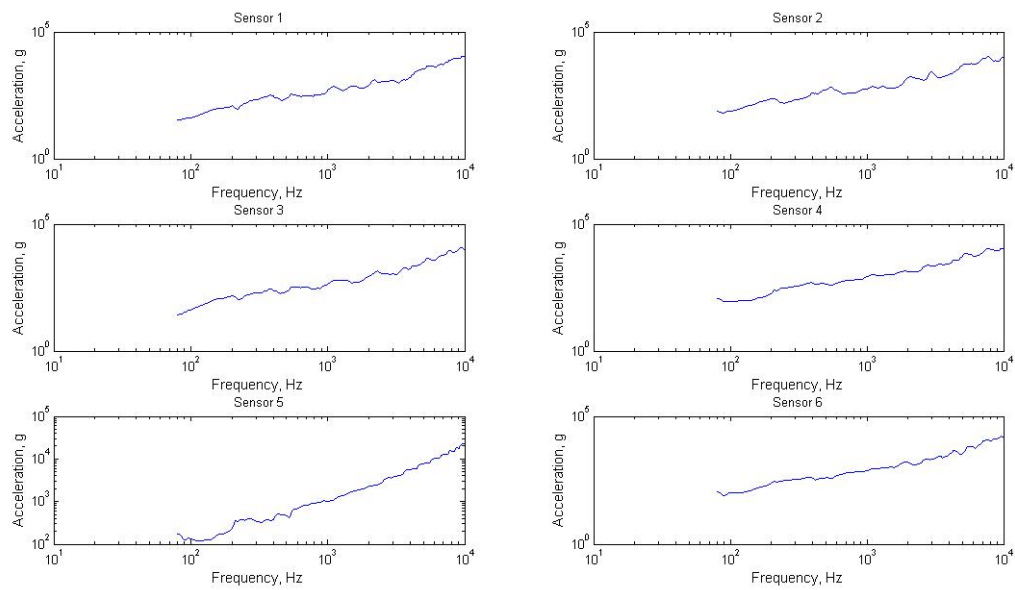


FIGURE 10: SRS SECOND SETUP

The highest acceleration corresponds to the sensor number five, the acceleration is going to be approximately of 30000 m/s^2 .

3 NUMERICAL SIMULATION

3.1 CODES

3.1.1 AUTODYN

AUTODYN software is used to analyze the behavior of materials under transient dynamic loading. It simulates non-linear impact phenomena involving large strains and deformations, plasticity, fracture and flow. Some examples are:

1. Hypervelocity impacts of space debris on a shielded spacecraft.
2. Explosive cutting and compaction.
3. Confined and unconfined explosions (underwater, underground and air).
4. Blast-structure interaction.
5. Impact and crush of a steel girder.

The dynamic behavior of a material is described by:

1. Conservation of mass
2. Conservation of momentum
3. Conservation of energy
4. Material models (Constitutive laws)
5. Initial conditions
6. Boundary conditions

All these equations are solved numerically in AUTODYN using explicit time integration and various solution techniques (named solvers in AUTODYN).

To carry out the resolution of the problem it is necessary to divide it into a finite number of easier problems. This process is called discretization. The equations need to be discretized in time and space. The discretization in time is the same regardless of the solver used (it is possible to specify the initial time step too). The main difference in the resolution of the problem is in the way the spatial discretization is done.

Alternative numerical processors are available and can be selectively used to model different regions of a problem. The AUTODYN solvers are:

1. Lagrange
2. ALE
3. Shell/Membrane
4. Beam/Truss/Spring/Damper
5. SPH
6. Euler
7. Euler-FCT
8. Multi-material Euler

The available processors include Lagrange for modeling solid continua and structures and Euler for modeling gases, fluids and the large distortion of solids. In Lagrange the grid moves and deforms with the material, the volume changes but not the mass, Euler solver uses a grid fixed

in the space, the material flows through the cell. AUTODYN includes also an ALE processor which can be used to provide automatic rezoning and is applicable to specialized flow problems. A Shell processor is available for modeling thin structures. Finally, an SPH (Smooth Particle Hydrodynamic) processor can be used for extreme solid deformations. Shocks are handled automatically and accurately. The codes include an erosion algorithm which enhances the ability of the Lagrange processor to simulate impact problems where large deformations occur. [2]

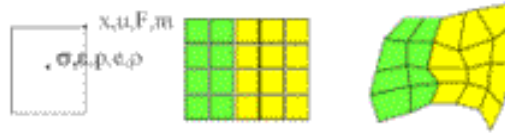


FIGURE 11: LAGRANGE SOLVER

ADVANTAGES	DISADVANTAGES
Fewer computations per cycle	Cell distortion leads to small time step
Clear definition of material interfaces and material boundaries	Cell distortion can lead to grid tangling
Good time history information	Thin sections need small time steps
Good for strength modeling	Complex logic for sliding interfaces
Less diffusion of shocks	
Simpler code	

TABLE 1: ADVANTAGES AND DISADVANTAGES OF LAGRANGE SOLVER

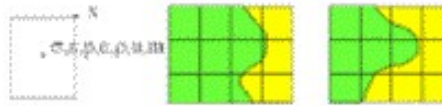


FIGURE 12: EULER SOLVER

ADVANTAGES	DISADVANTAGES
No grid distortions	More computations per cycle
Large deformations	Diffusion of material boundaries
Higher time step in general	Less flexible for strength modeling
	Thin sections need small time steps.
	Shocks diffused more than Lagrange

TABLE 2: ADVANTAGES AND DISADVANTAGES OF EULER SOLVER

3.1.2 ANSYS

ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems such as static and dynamic structural analysis (linear and non-linear), heat transfer, fluid problems, acoustic and electromagnetic problems. ANSYS uses the finite-element method to solve the underlying governing equations and the associated problem-specific boundary conditions.

Finite element analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements. The software implements equations that govern the behaviour of these elements and solves them all creating a comprehensive

explanation of how the system acts as a whole. These results then can be presented in tabulated or graphical forms.

ANSYS has three different modules: pre-processing (geometry creation, meshing), solver and post-processing modules in a graphical user interface.

1. Pre-processing: used to define the problem.
 - Define key points/lines/areas/volumes
 - Define element type and material and geometric properties
 - Mesh lines/areas/volumes
2. Solver: assign loads, constraints and solve.
3. Post-processing: further processing and viewing of the results.

The set of solutions offered by ANSYS can be defined as integrated, modular and extensible.

It is integrate because it allows the generation of synergies between various technologies required to develop a product without leaving the platform. Its level of integration can be used from the most advanced CAD systems with the possibility of bi-directional and associative information transfer.

The modularity of ANSYS allows many users begin installing an application for the initial analysis of its components under simple working hypotheses. As the design progresses and confidence in the solution increases, more complicated tests are needed to reach the validation process.

ANSYS is extensible because it allows the development of vertical applications or adaptations of the program to the specific needs of each user. These adaptations range from simple standardization of the methodology of calculation or the automatic generation of standard report according to required specification, to the generation of highly specialized tools tailored to a particular industry or specific applicability.

3.1.3 CONWEP

CONWEP is an empirically based loading model which calculates a range of blast effects from different types of high explosives and weapons. CONWEP contains a compilation of data from explosive tests using charge weights from less than 1kg to over 400000kg. The results achieved using CONWEP are they all based on experimental tests so they are supposed not to be definitely. However, the pressure results given by AUTODYN are going to be compared with those given by CONWEP in order to see if the peak pressure obtained is, at least, similar.

3.2 NUMERICAL SIMULATION WITH AUTODYN

3.2.1 FIRST MODELING

The first objective is to model the setup in order to be able to represent it in AUTODYN and ANSYS and achieve the real accelerations.

The first setup consists of two plates of steel separated 0.080 m of dimensions 1mx1mx0.01m. The plate from above suffers the high accelerations while on the one from below lays the detonating cord.

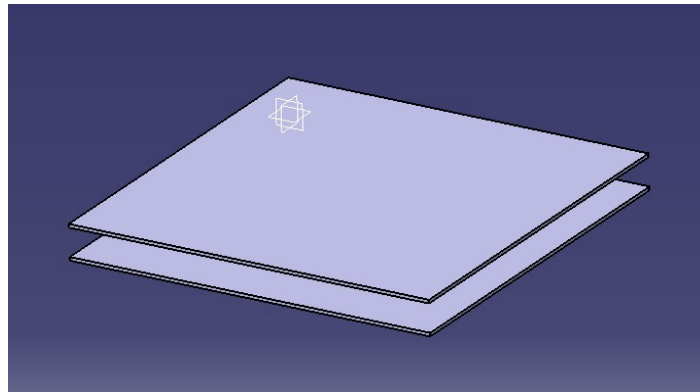


FIGURE 13: FIRST MODELING

To achieve the correct accelerations the first setup will be modeled as two plates (1mx1mx0.01m) of steel 4340 separated 0.080 m. The two plates are placed in a volume of air (considered as an ideal gas). A non-flow out condition replaces the plate from below in order to speed up the problem. The non-flow out condition means that the shock wave it is not able to go through the place where the plate from below was supposed to be.

The volume of air used is a box that will be divided into different numbers of cells to find out how the results change with the number of cells.

The explosion is an unconfined explosion because it takes place in the air. Due to this reason, the detonation of the explosion and the propagation of the wave should be modeled at a distance less than the 0.8 m which separates the two plates.

Because of the study of the detonation it is known that the shock waves spread under the form of spheres. The centre of these shock waves is the initial point of detonation. Due to the spherical symmetry the explosion can be modeled as a wedge with an axial symmetry. For the model to be faster, instead of using directly the explosive it is used a wedge which allows to have the same pressure the explosive will cause on the plate.

The explosive should be modeled as a cylinder but, as it is very difficult to design it this way, three spheres of TNT are used. The detonating cord replaced has a length of 0.05 m so the three spheres must be spaced to 0.0165 m, thus occupying the entire length of the detonator cord.

$$0.0165 \cdot 3 = 0.0495m \cong 0.05m$$

0.05 kg and 0.1 kg of TNT are used, due to the reflections the calculations should be done with the double of these quantities, 0.1 kg and 0.2 kg.

0.05 KG OF TNT

For 0.05 kg of TNT or 0.1kg of TNT due to the reflections:

$$\frac{0.1kg}{3spheres} = 0.033kg / sphere$$

$$\frac{4}{3}\pi r^3 = \frac{0.033kg}{1630kg / m^3} \Rightarrow r = 0.0169585m$$

As it is necessary to have 20 cells at least for the simulation to be correct

$$\frac{0.0169585m}{20} = 0.0008479m$$

The dimensions of the cells should be 0.0008479 m or even less, in order to use an easier value, 0.0008 m is chosen.

For the wedge with a length of 0.080 m

$$\frac{0.08m}{0.0008m} = 100cells$$

In short:

- Radius of the spheres: 0.0169585 m.
- Number of cells for the wedge: 100 cells.
- Dimension of the cell: 0.0008 m.

It is important to stop the simulation before the shock wave arrives at the end of the wedge. Due to this reason the results of the cycle 576 will be used.

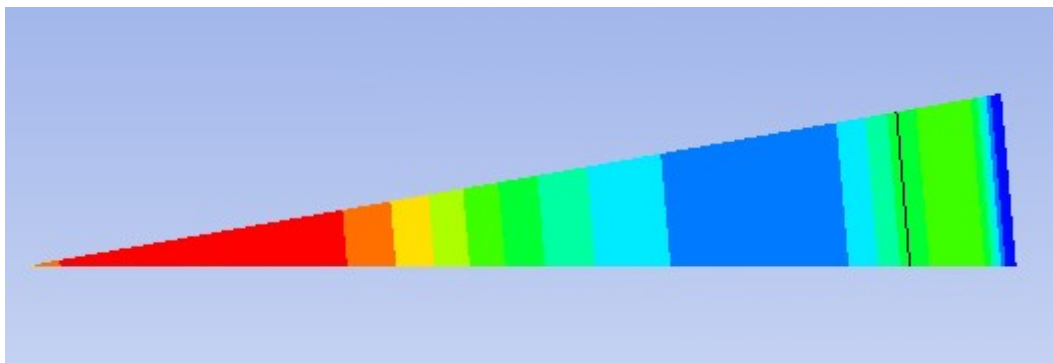


FIGURE 14: WEDGE FOR 50 G TNT

0.1 KG OF TNT

For 0.1 kg (0.2 kg due to the reflections) proceeding in the same way as before, the following results will be obtained:

- Radius of the spheres: 0.0213735 m.
- Number of cells for the wedge: 80 cells.
- Dimension of the cell: 0.001 m.

The results of the cycle 551 will be used because it is the cycle just before the shock wave arrives at the end of the wedge.

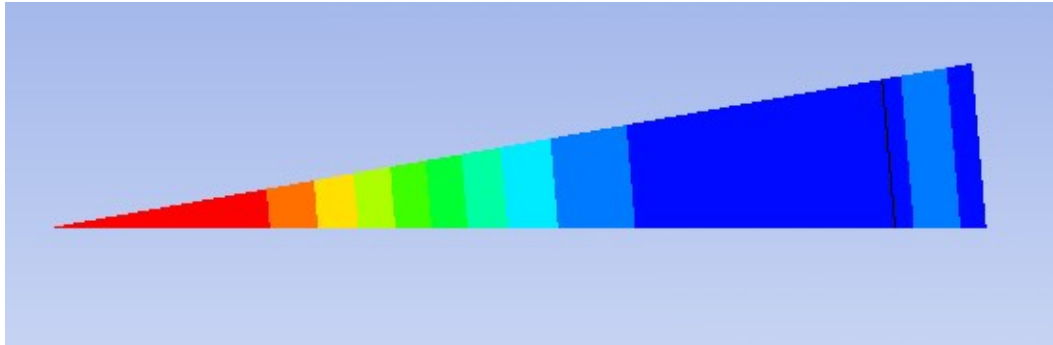


FIGURE 15: WEDGE FOR 100 G TNT

AUTODYN has the option to use the “remapping”. The remapping consists of using the solutions achieved in 2D or 1D and impose them to the 3D or 2D problem. It is possible to simulate the explosion in 1D and then export it to the 3D case, thus the resolution of the explosion will be faster.

Three wedges will replace the three spheres in the following positions.

	Sphere 1	Sphere 2	Sphere 3
X origin (m)	0.500	0.500	0.500
Y origin (m)	0.335	0.500	0.665
Z origin (m)	0	0	0

TABLE 3: POSITION OF THE SPHERES

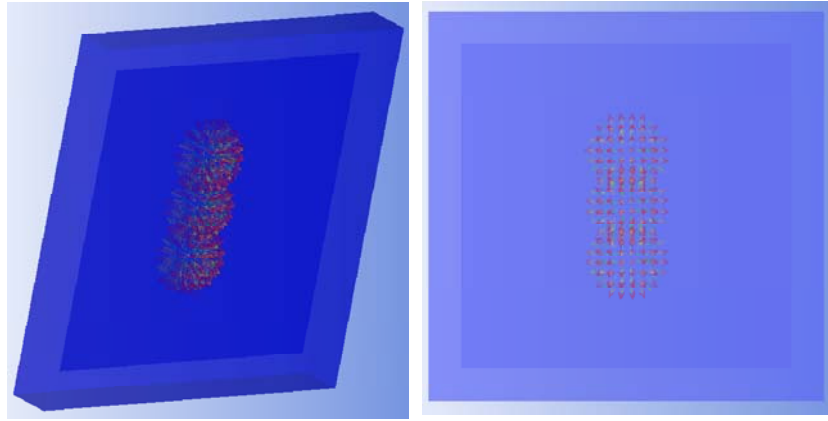


FIGURE 16: POSITION OF THE EXPLOSIVE

The figure shows the vectors of the three wedges, one for each of the three spheres of explosive which represent the 0.050 m of length (50 g of TNT) of the detonating cord.

There are not initial conditions, just boundary conditions:

1. Flow out: The flow out conditions allow the shock wave to go through the limits of the volume of air that surround the plate.

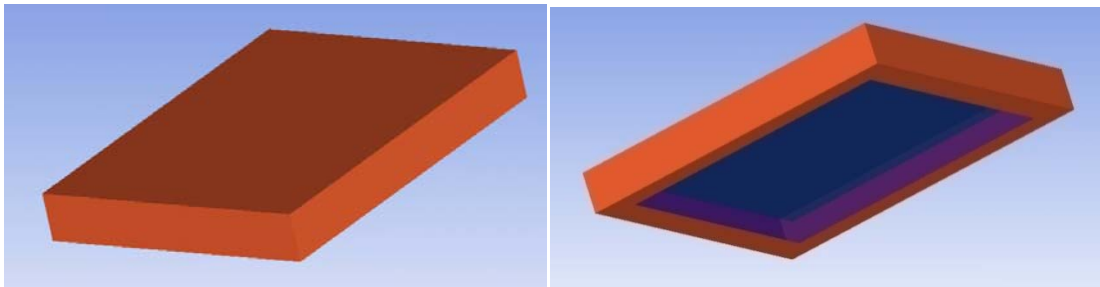


FIGURE 17: FLOW OUT (BOUNDARY CONDITION)

The gauges are situated on the plate above. The gauges are used to know the value of the accelerations that are numerically achieved. There are 25 gauges, number 8, 13 and 18 are just above the explosive. To represent the accelerometers two more gauges are added (gauges number 26 and 27). (See figure below)

The positions of the accelerometers in the experimental test are:

	Accelerometer 1	Accelerometer 2
X (m)	0.740	0.860
Y (m)	0.860	0.140
Z (m)	0.080	0.080

TABLE 4: POSITIONS FOR THE ACCELEROMETERS

The reason why these accelerometers are placed here is because of the reproducibility test that were realized the previous years.

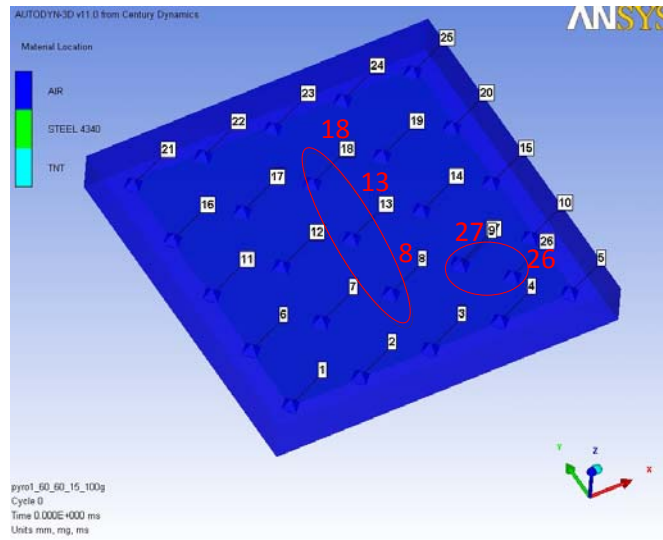


FIGURE 18: GAUGES IN THE PLATE

The same number of gauges is added in the air just below the ones on the plate, at a height of 0.07901 m. These gauges are numbered from 28 to 53, including the gauges in the positions of the accelerometers. With these gauges it is possible to know the value of the pressure that the plate is suffering and the place where the pressure is higher. It is important to know the value of the pressure to compare it with the value of the pressure obtained from CONWEP and be capable to know if the pressures achieved with AUTODYN are close to reality and in this way be more certain about obtaining good results for the accelerations.

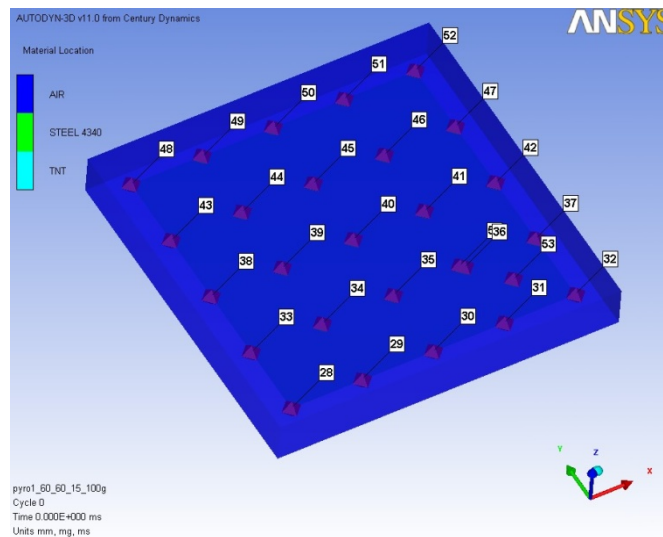


FIGURE 19: GAUGES IN THE AIR

3.2.1.1 SOLVER EULER-LAGRANGE

3.2.1.1.1 MODEL 1:

1. Amount of explosive : 0.05 Kg TNT
2. Mesh of air of dimension: $1.2 \times 1.2 \times 0.15 \text{ m}^3$
 - In X and Y: 60 cells. Dimension of the cell: 0.020 m.
 - In Z: 15 cells. Dimension of the cell: 0.010 m.

3. Plate of steel 4340 of dimension: $1 \times 1 \times 0.1 \text{ m}^3$
 - In X and Y: 200 cells. Dimension of the cell: 0.005 m.
 - In Z: Shell of 0.01 m of thickness.
4. Three wedges of 0.033 kg separated 0.165 m in order to comply with the 0.5 m of the detonating cord.
 - Length of the wedges: 0.08 m, distance between the test plates.
 - 0.033 kg of TNT. Radius: 0.016585 m. Dimension of the cell: 0.0008 m.

RESULTS

1. The maximum value of the pressure is 39340000 Pa (cycle 101). This maximum pressure is reached in the gauge 40 which is the one just below the gauge in the middle of the shock plate (gauge 13)
2. Displacements, velocities and accelerations:
 - Gauges 8, 13 and 18: Gauges situated on the shock plate just above the explosive.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 8	0.041239 m	7.1553 m/s	204.99 m/s^2
Gauge 13	0.041974 m	12.699 m/s	449.16 m/s^2
Gauge 18	0.037002 m	7.7011 m/s	254.61 m/s^2

TABLE 5: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

The displacements, velocities and accelerations for gauges 8, 13 and 18 are shown in figure 20. The maximum displacement, velocity and acceleration can be seen in table 5 and in the figure below.

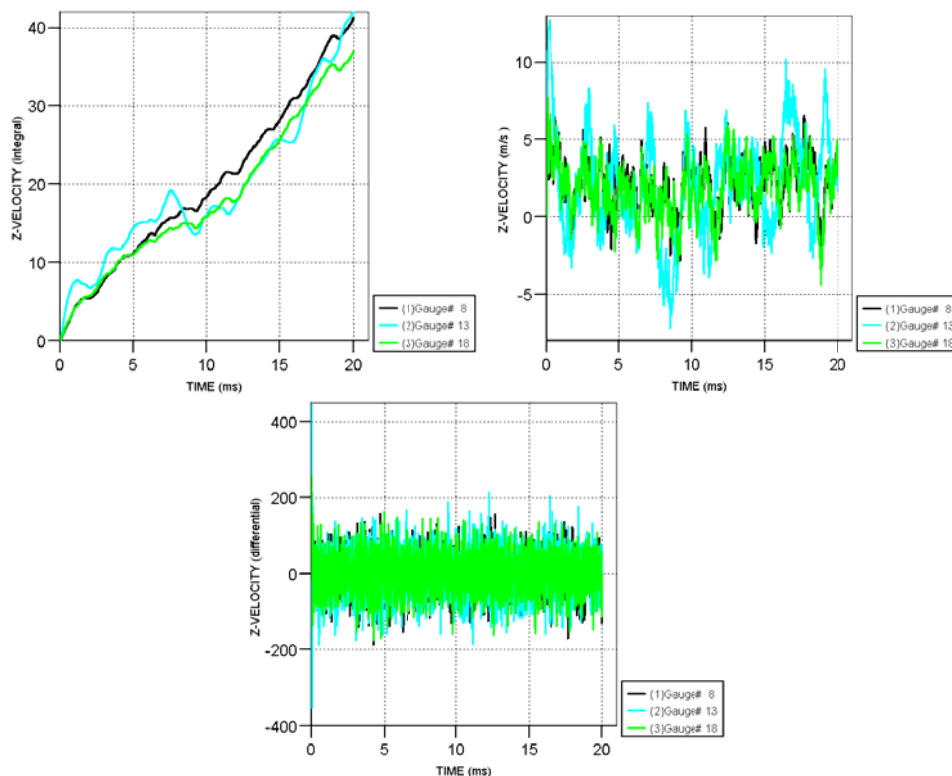


FIGURE 20: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18

- Gauges 26 and 27 represent the accelerometers 2 and 1.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.036593 m	6.0864 m/s	101.43 m/s ²
Gauge 27	0.038903 m	5.4852 m/s	103.81 m/s ²

TABLE 6: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

In figure 21 the displacements, velocities and accelerations for gauges 26 and 27 (the ones which represent the accelerometers) are presented.

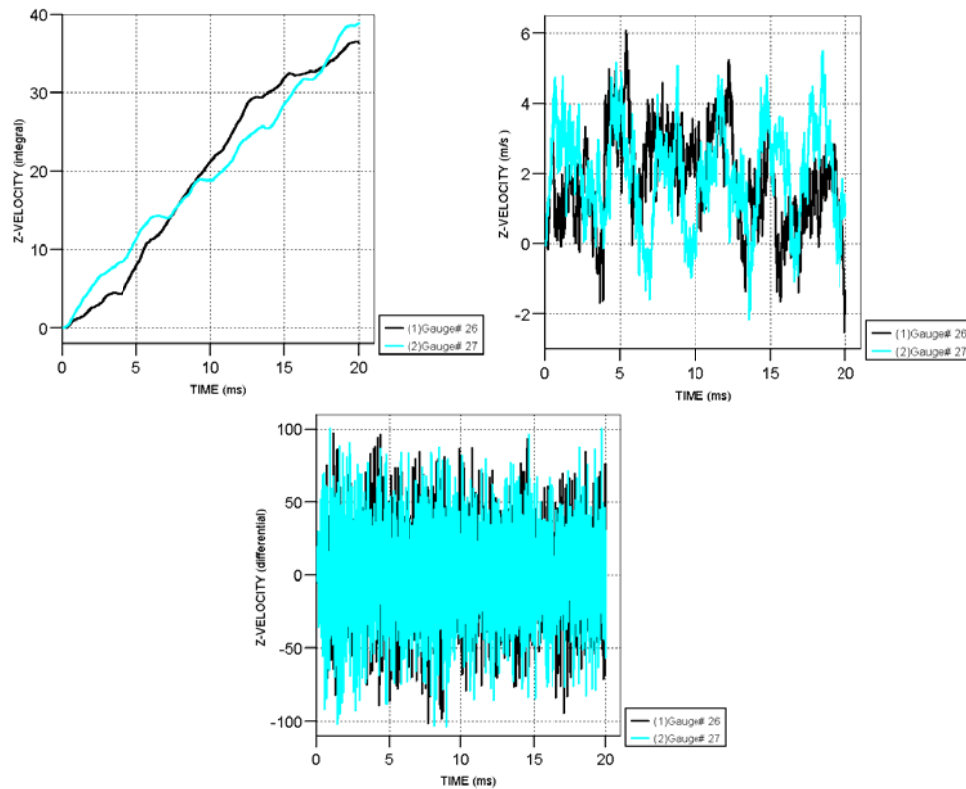


FIGURE 21: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

OBSERVATIONS

1. The displacements, velocities and accelerations are very far from the experimental ones. They are lower than they were supposed to be. The highest value for the acceleration is 449.16 m/s² in the gauge 13, the one in the middle of the plate. The acceleration of gauges 26 and 27 is around 100 m/s² while it should be near 18000 m/s².
2. The graphs for the accelerations are not similar to the graphs coming from the experimental tests. In these there is an attenuation in the accelerations while in the numerical simulations the accelerations don't experience any decrease. This result is understandable because the damping factor hasn't been introduced yet.

3.2.1.1.2 MODEL 2

The model is the same as the first one but with a different number of cells in each direction of the mesh of the air. The number of cells has been increased in order to see if, with a finer mesh, the results are closer to the experimental values or, on the contrary, the results don't depend on the size of the cells.

1. Amount of explosive: 0.05 kg TNT
2. Mesh of air of dimension: $1.2 \times 1.2 \times 0.150 \text{ m}^3$
 - In X and Y: 80 cells. Dimension of the cell: 0.015 m.
 - In Z: 20 cells. Dimension of the cell: 0.0075 m.
3. Plate of steel 4340 of dimension: $1 \times 1 \times 0.01 \text{ m}^3$
 - In X and Y: 200 cells. Dimension of the cell: 0.005 m.
 - In Z: Shell of 0.01 m of thickness.
4. Three wedges of 0.033 kg separated 0.165 m in order to comply with the 0.5 m of the detonating cord.
 - Length of the wedges: 0.08 mm, distance between both of the plates.
 - 0.033kg of TNT. Radius: 0.016585 m. Dimension of the cell: 0.0008 m.

RESULTS

1. Value of the maximum pressure 46600000 Pa (cycle 76). This value is reached in the gauge 40 , the one just below the gauge in the middle of the shock plate (gauge 13)
2. Displacements, velocities and accelerations:
 - Gauges 8, 13 and 18: Gauges situated on the plate just above the explosive.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 8	0.059238 m	6.7662 m/s	174.93 m/s^2
Gauge 13	0.063427 m	13.192 m/s	410.46 m/s^2
Gauge 18	0.059833 m	6.8865 m/s	206.71 m/s^2

TABLE 7: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

The displacements, velocities and accelerations of gauges 8, 13 and 18 are shown in figure 22.

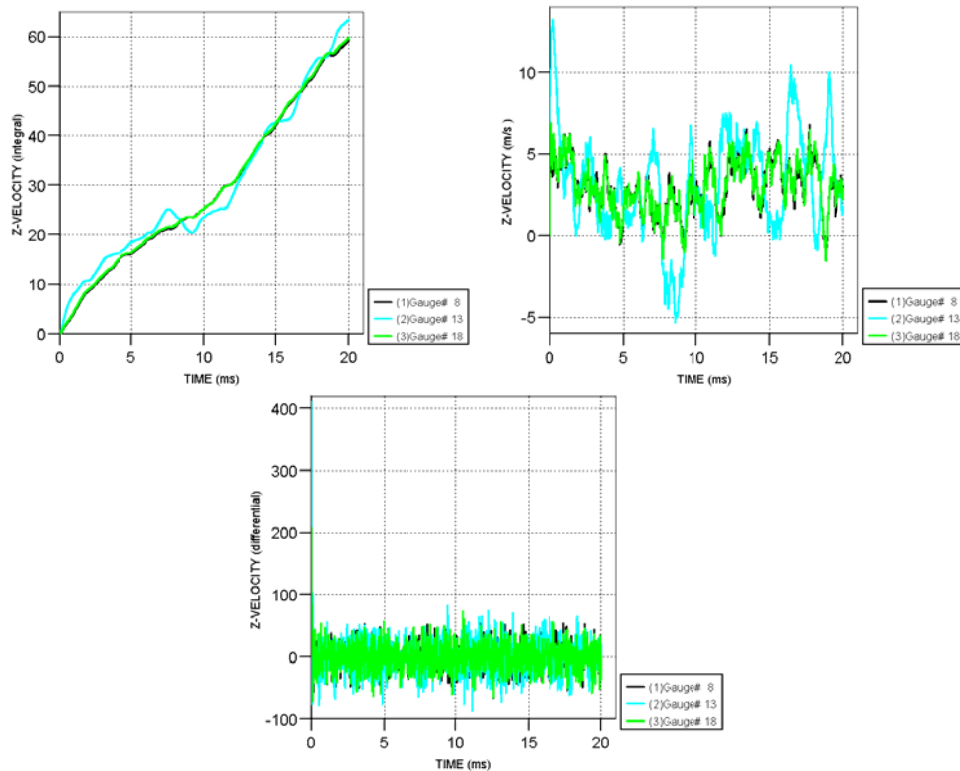


FIGURE 22: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

- Gauges 26 and 27 represent the accelerometers 2 and 1.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.053369 m	6.7891m/s	46.984 m/s ²
Gauge 27	0.057029 m	5.7272 m/s	39.908 m/s ²

TABLE 8: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

From left to right in the figure below, the displacements, velocities and accelerations of gauges 26 and 27 on the plate are shown.

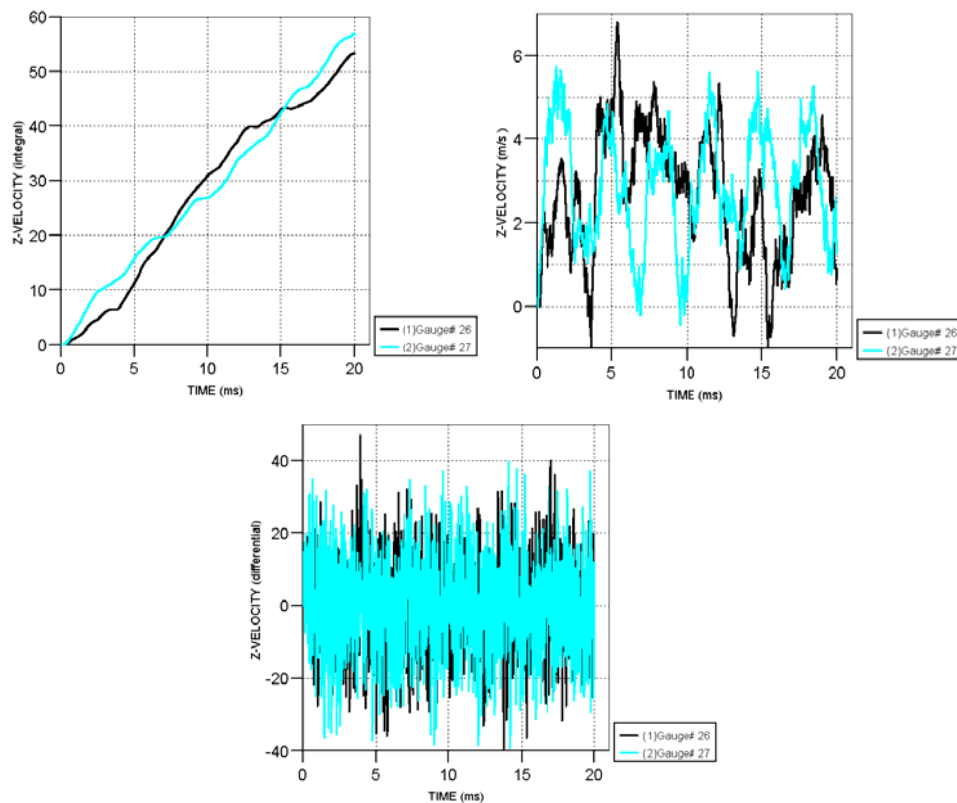


FIGURE 23: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

OBSERVATIONS

1. The values of the displacements, velocities and accelerations are not close to the experimental values. As in the previous case the accelerations reached are lower than they should be, even lower than before. The values are now 46.984 m/s² and 39.908 m/s² instead of 17900 m/s² and 18830 m/s².
2. The profile of the accelerations is not the one searched, there is not an attenuation in the profile of the accelerations. The reason is that the damping factor is not used.

3.2.1.1.3 MODEL 3

1. Amount of explosive: 0.1 kg TNT
2. Mesh of air of dimension: 1.2x1.2x0.15 m³
 - In X and Y: 60 cells. Dimension of the cell: 0.020 m.
 - In Z: 15 cells. Dimension of the cell: 0.010 m.
3. Plate of steel 4340 of dimension: 1x1x0.1 m³
 - In X and Y: 200 cells. Dimension of the cell: 0.005 m.

- In Z: Shell of 0.01 m of thickness.
- Three wedges of 0.066 kg separated 0.165 m in order to comply with the 0.5 m of the detonation cord.
 - Length of the wedges: 0.080 m, distance between both of the plates.
 - 0.066 kg of TNT. Radius: 0.0213735 m. Dimension of the cell: 0.001 m.

RESULTS

- Maximum value of pressure: 69600000 Pa, reached in cycle 101 in the gauge 40 (the one below the gauge 13 which is in the middle of the shock plate)
- Displacements, velocities and accelerations:
 - Gauges 8, 13 and 18: Gauges situated on the plate just above the explosive.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 8	0.11154 m	13.331 m/s	292.62 m/s ²
Gauge 13	0.11637 m	26.065 m/s	513.18 m/s ²
Gauge 18	0.11463 m	13.530 m/s	370.52 m/s ²

TABLE 9: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

The displacements, velocities and accelerations for gauges 8, 13 and 18 are presented in figure 24. The maximum values for these three variables are shown in table 9.

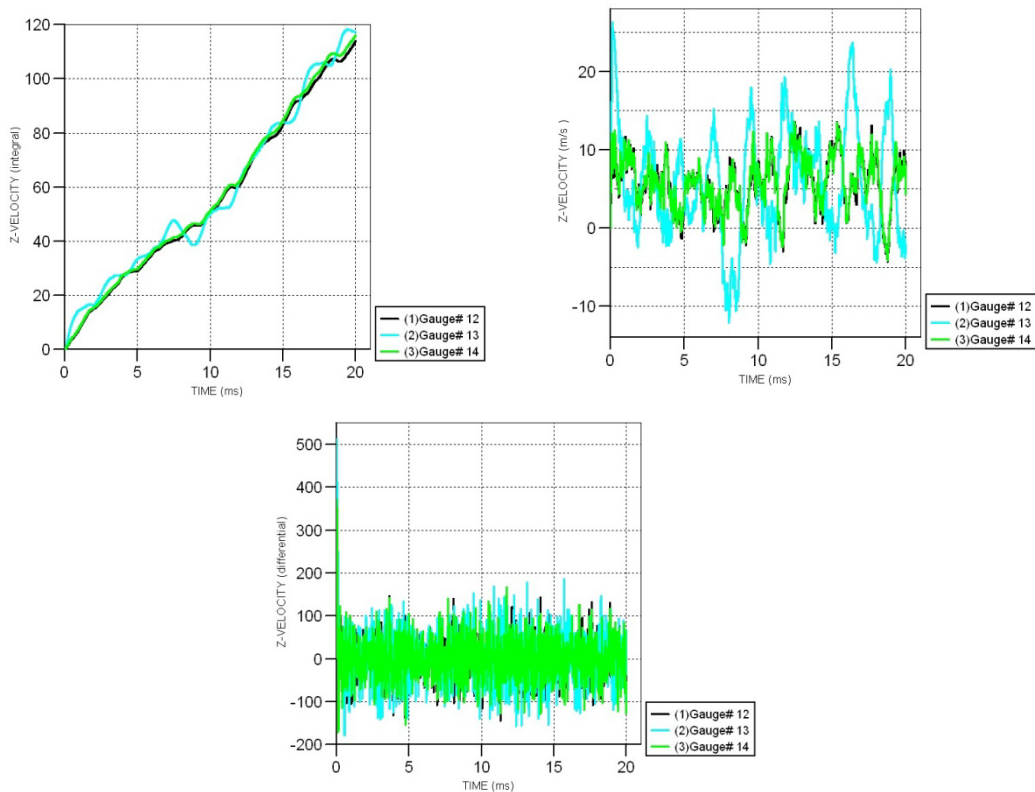


FIGURE 24: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

- Gauges 26 and 27 represent the accelerometers 2 and 1.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.10335 m	12.086 m/s	123.81 m/s ²
Gauge 27	0.10719 m	13.424 m/s	88.613 m/s ²

TABLE 10: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

The graphs in the figure 25 refer to the displacements, velocities and accelerations the gauges which represent the accelerometers suffer.

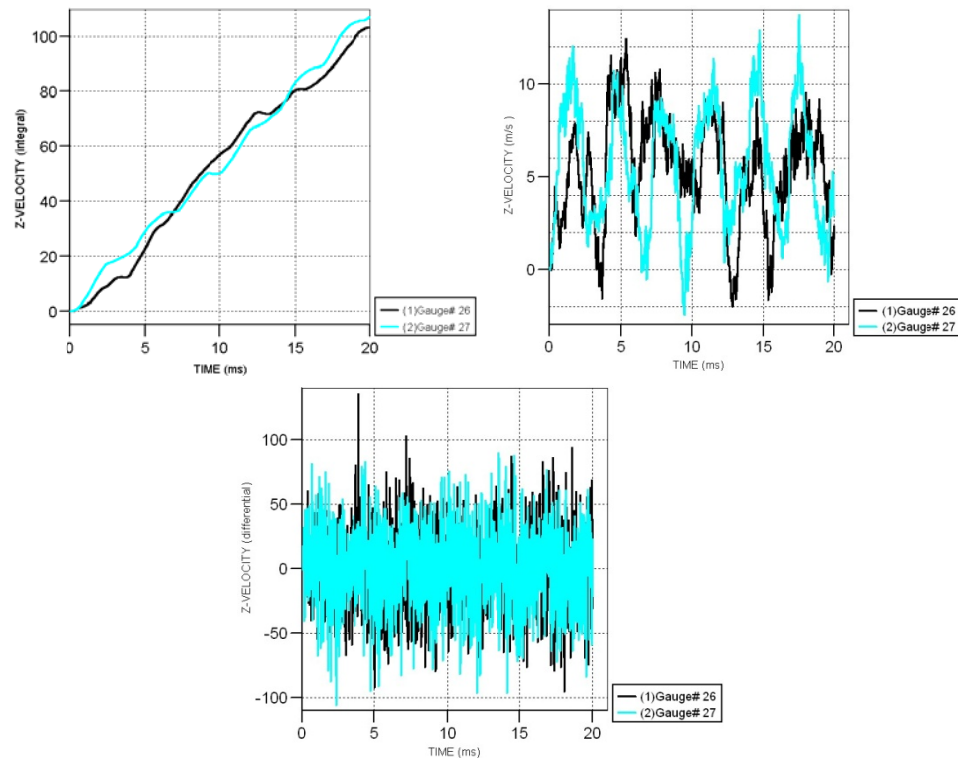


FIGURE 25: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

OBSERVATIONS

1. Despite the increase of the amount of explosive used, the maximum value of the displacements, velocities and accelerations doesn't match the experimental results. The highest value for the accelerometers is 123.81 m/s² while it should be around 18000 m/s². It is true that the value of the acceleration is higher than the one in the first model (same mesh but 0.05 kg of TNT instead of 0.1 kg) but just 20 m/s² more.
2. The profile of the accelerations doesn't look similar to the experimental profile because the damping factor has not been applied yet.

3.2.1.1.4 MODEL 4

1. Amount of explosive: 0.1 kg TNT
2. Mesh of air of dimension: 1.2x1.2x0.150 m³
 - In X and Y: 80 cells. Dimension of the cell: 0.015 m.
 - In Z: 20 cells. Dimension of the cell: 0.0075 m.
3. Plate of steel 4340 of dimension: 1x1x0.01 m³
 - In X and Y: 200 cells. Dimension of the cell: 0.005 m.

- In Z: Shell of 0.01 m of thickness.
- Three wedges of 0.066 kg separated 0.165 m in order to comply with the 0.5 m of the detonation cord.
 - Length of the wedges: 0.080 m, distance between both of the plates.
 - 0.066 kg of TNT. Radius: 0.0213735 m. Dimension of the cell: 0.001 m.

RESULTS

- The maximum value of pressure is 83590000 Pa. It is reached in the cycle 76 in gauge 40 (the one below gauge 13 which is in the middle of the plate)
- Displacements, velocities and accelerations:
 - Gauges 8, 13 and 18: Gauges situated on the plate just above the explosive.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 8	0.09770 m	12.400 m/s	292.70 m/s ²
Gauge 13	0.10146 m	24.771 m/s	758.09 m/s ²
Gauge 18	0.07909 m	13.032 m/s	359.71 m/s ²

TABLE 11: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

The displacements, velocities and accelerations of gauges 8, 13 and 18 can be seen in the figure below, figure 26.

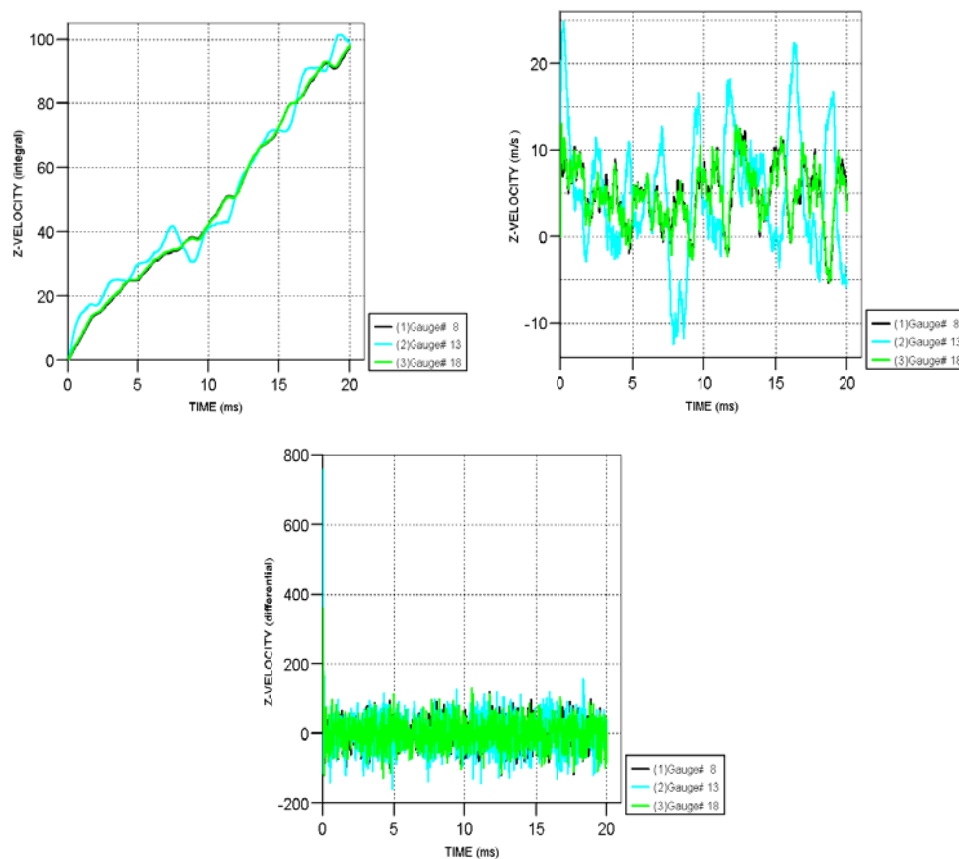


FIGURE 26: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.

- Gauges 26 and 27 represent the accelerometers 2 and 1.

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.090127 m	11.889 m/s	82.467m/s ²
Gauge 27	0.092958 m	11.973 m/s	80.456 m/s ²

TABLE 12: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

The displacements, velocities and accelerations the gauges 26 and 27 suffer are shown in the graphs below.

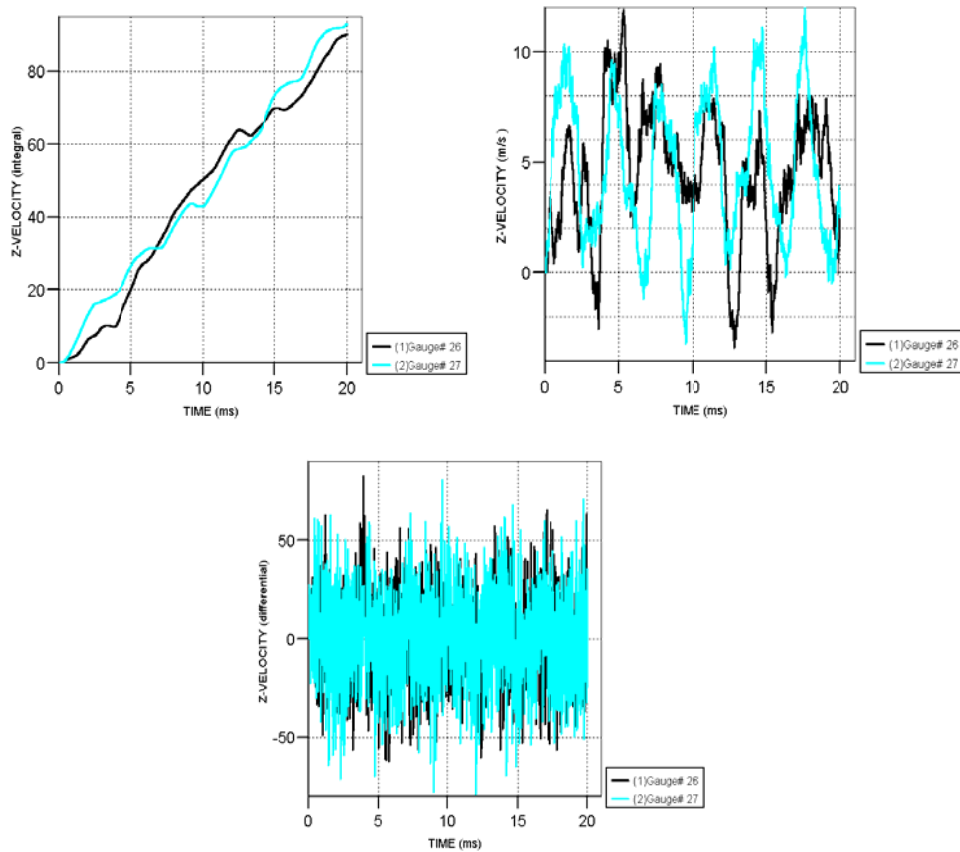


FIGURE 27: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

OBSERVATIONS

1. The value of the numerically accelerations doesn't reach the value of the experimental ones although the amount of explosive has been increased. Higher values than those for 0.05 kg for the same mesh are obtained but for the same quantity of TNT the finer mesh causes lower accelerations.
2. The profile of the accelerations is not correct, there is not an attenuation in the profile of the accelerations. As in the previous models the damping factor is not used yet.

	DISPLACEMENTS				VELOCITIES				ACCELERATIONS			
	50 g		100g		50 g		100g		50 g		100g	
	60_60_15	80_80_20	60_60_15	80_80_20	60_60_15	80_80_20	60_60_15	80_80_20	60_60_15	80_80_20	60_60_15	80_80_20
Gauge 8	0.041239 m	0.059238 m	0.11154 m	0.09770 m	7.1553 m/s	6.7662 m/s	13.331 m/s	12.400 m/s	204.99m/s ²	174.93m/s ²	292.62 m/s ²	292.70 m/s ²
Gauge 13	0.041974 m	0.063427 m	0.11637 m	0.10146 m	12.699 m/s	13.192m/s	26.065 m/s	24.771 m/s	449.16 m/s ²	410.46 m/s ²	513.18 m/s ²	758.09 m/s ²
Gauge 18	0.037002 m	0.059833 m	0.11463 m	0.07909 m	7.7011 m/s	6.8865 m/s	13.530 m/s	13.032 m/s	254.61 m/s ²	206.71 m/s ²	370.52 m/s ²	359.71 m/s ²
Gauge 26	0.036593 m	0.053369 m	0.10335 m	0.090127 m	6.0864 m/s	6.7891m/s	12.086 m/s	11.889 m/s	101.43 m/s ²	46.984 m/s ²	123.81 m/s ²	82.467 m/s ²
Gauge 27	0.038903 m	0.057029 m	0.10719 m	0.092958 m	5.4852 m/s	5.7272 m/s	13.424 m/s	11.973 m/s	103.81 m/s ²	39.908 m/s ²	88.613 m/s ²	80.456 m/s ²

TABLE 13: SUMMARY OF THE DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 26 AND 27

OBSERVATIONS

1. With the increase of the amount of explosive, the value of the accelerations is higher but not as higher as it should be. The value of the accelerations is still far from the value of the real ones.
2. Increasing the number of cells in the air, the value of the accelerations decreases except for the gauge 13 in the last model.
3. The accelerations for all the models used don't have the correct profile of accelerations because the damping factor has not been applied yet.

3.2.1.2 SOLVER: LAGRANGE-BOUNDARY CONDITIONS

Due to the very low values of acceleration obtained with the modeling of the explosive in AUTODYN, its effect will be replaced by the pressure profile applied as a boundary condition on the shock plate. Different pressures are going to be applied in the zone where the detonating cord is supposed to be.

3.2.1.2.1 MODEL 1

The figure 28 shows the first pressure applied, a triangular profile. Because of CONWEP it is known that the maximum pressure for one sphere of 0.02 kg is 114000000 Pa. Instead of using three spheres of 0.033 kg in order to have 0.1kg of C4, 5 spheres of 0.02 kg are used. Thus, the pressure won't be as high as it would be and the possibilities of the plate to plasticize will be less. The characteristics of the pressure that is going to be applied can be seen in the table below.

	Peak pressure (Pa)	Start time (s)	Peak time (s)	End time (s)
Triangular	114000000	0	0	0.00005

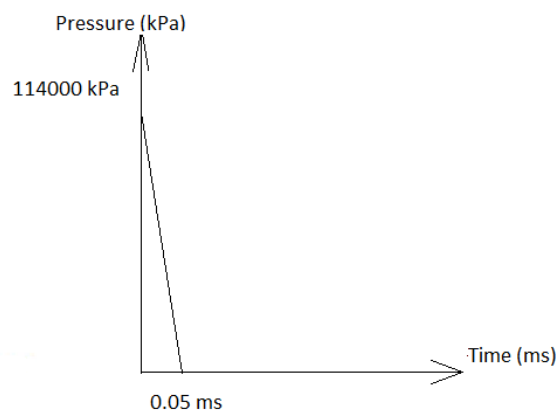


FIGURE 28: REPRESENTATION OF THE PRESSURE

The pressure is going to be applied to an area which includes the gauges 3, 8, 13, 18 and 23 to have a similar area to the one where the detonating cord was. In this way it will be possible to make a better comparison between the experimental results and the numerical ones.

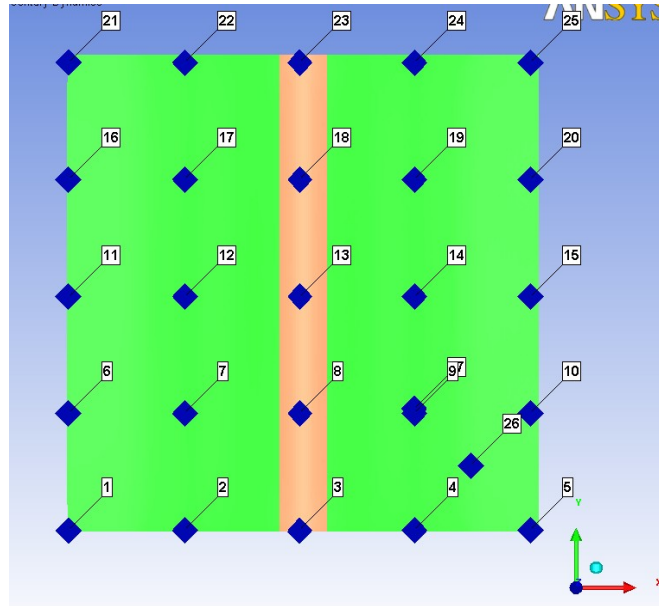


FIGURE 29: ZONE WHERE THE PRESSURE IS APPLIED

The accelerations of the gauges 3, 8, 13, 18 and 23 (where the pressure is applied) and of gauges 26 and 27 (accelerometers) are going to be studied in the next sections.

RESULTS

1. Displacements, velocities and accelerations:

- Gauges 3, 8, 13, 18 and 23

	Max. displacement	Max. velocity	Max. acceleration
Gauge 3	0.045706 m	41.324 m/s	1393.2 m/s ²
Gauge 8	0.043315 m	39.721 m/s	1393.2 m/s ²
Gauge 13	0.042714 m	39.721 m/s	1393.2 m/s ²
Gauge 18	0.043294 m	39.721 m/s	1393.2 m/s ²
Gauge 23	0.045424 m	40.167 m/s	1393.2 m/s ²

TABLE 14: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

The graphs below show the displacements, velocities and accelerations of gauges 3, 8, 13, 18 and 23, the gauges just in the middle of the plate.

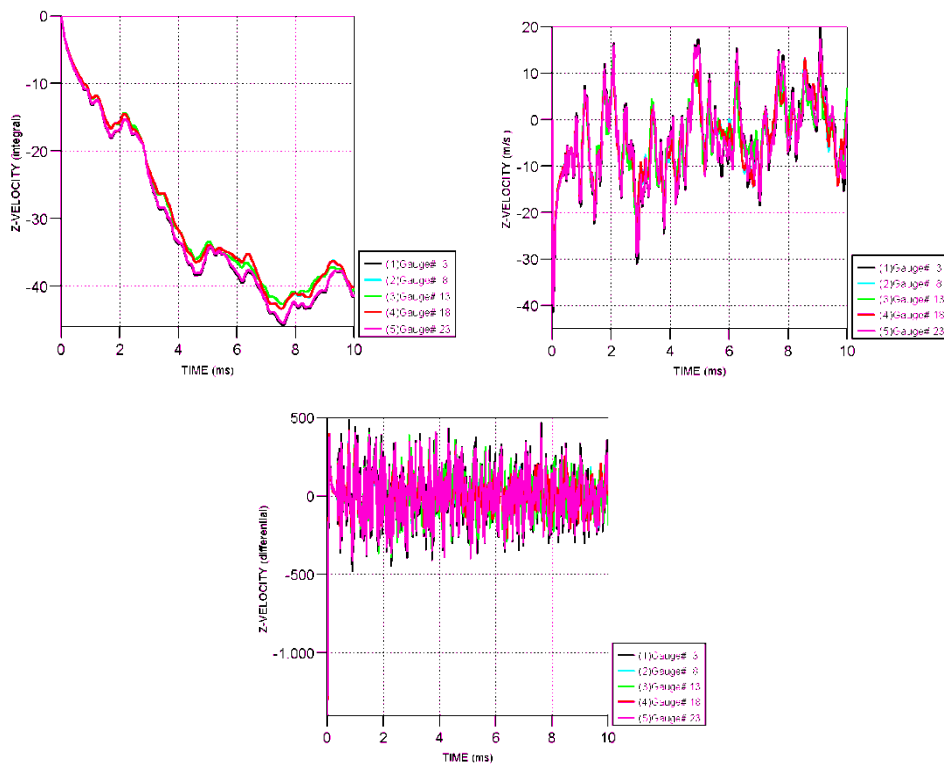


FIGURE 30: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

- Gauges 26 and 27

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.035010 m	16.136 m/s	332.98 m/s ²
Gauge 27	0.037865 m	16.151 m/s	377.74 m/s ²

TABLE 15: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

The figure 31 represents from left to right the displacements, velocities and accelerations of gauges 26 and 27.

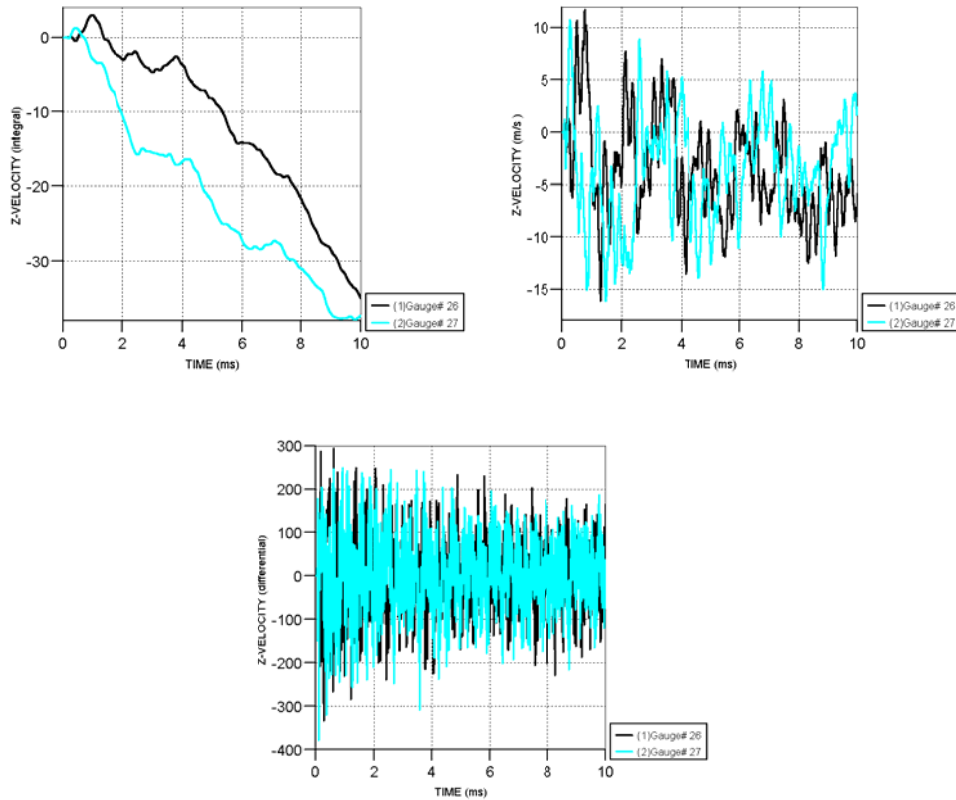


FIGURE 31: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

2. The plate is plasticized (different from the real behavior of the plate)

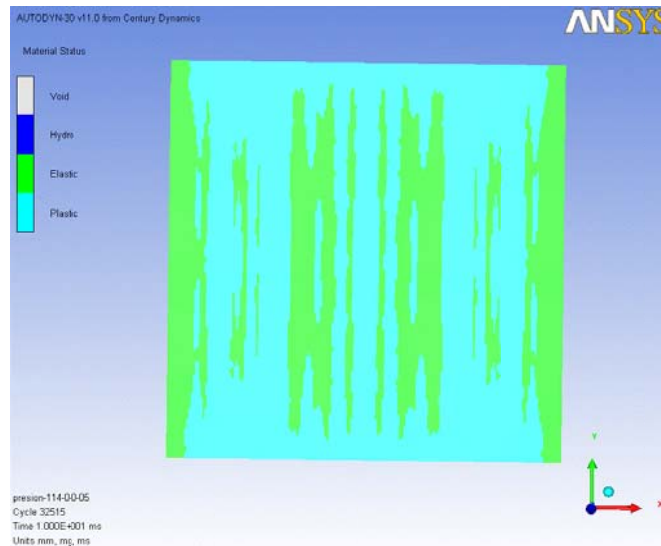


FIGURE 32: BEHAVIOR OF THE PLATE

OBSERVATIONS

1. The displacements, velocities and accelerations are still far from the experimental values. They are closer than in the previous models (the value of the accelerations is three times the value obtained) but they don't reach the correct ones.
2. Because of the high value of the pressure, most of its energy is used to plasticize the plate instead of using it to move the plate. The value of the pressure is going to be

decreased to study if the pressure of 77800000Pa (for one sphere of 0.01 kg) also plasticizes the plate.

3.2.1.2.2 MODEL 2

The pressure, given by CONWEP, caused by the explosion of 0.01 kg (5 spheres of 0.01kg in order to have 0.05 kg) is 77800000 Pa. Introducing this value as the boundary condition, the accelerations and the behavior of the plate are going to be studied.

	Peak pressure (Pa)	Start time (s)	Peak time (s)	End time (s)
Triangular	77800000	0	0.0001	0.0002

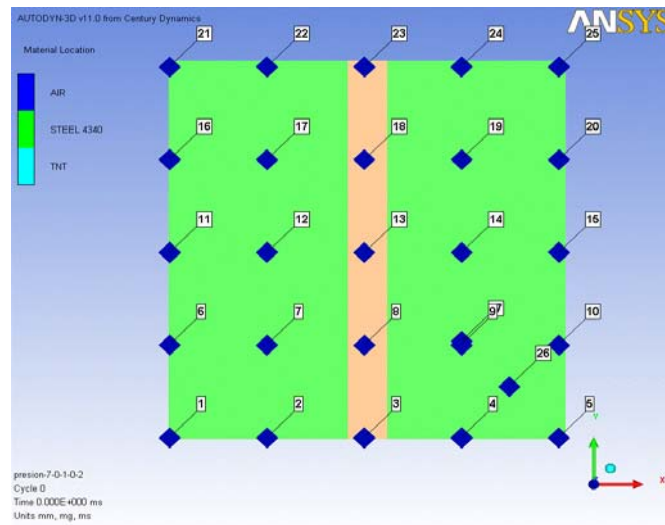


FIGURE 33: ZONE WHERE THE PRESSURE IS APPLIED

RESULTS

1. Displacements, velocities and accelerations:

- Gauges 3, 8, 13, 18 and 23

	Max. displacement	Max. velocity	Max. acceleration
Gauge 3	0.24063 m	86.411 m/s	910.61 m/s ²
Gauge 8	0.24032 m	82.071 m/s	868.98 m/s ²
Gauge 13	0.24029 m	82.075 m/s	869.20 m/s ²
Gauge 18	0.24031 m	82.076 m/s	869.26 m/s ²
Gauge 23	0.24019 m	83.906 m/s	891.31 m/s ²

TABLE 16: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

Displacements, velocities and accelerations of gauges 3, 8, 13, 18 and 23 are presented in figure 34.

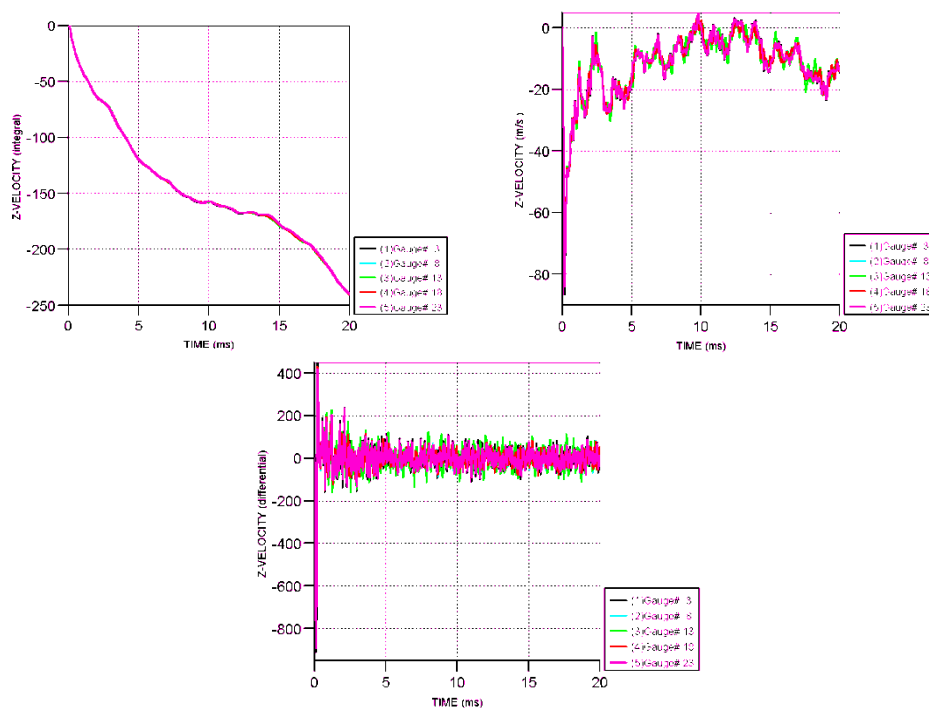


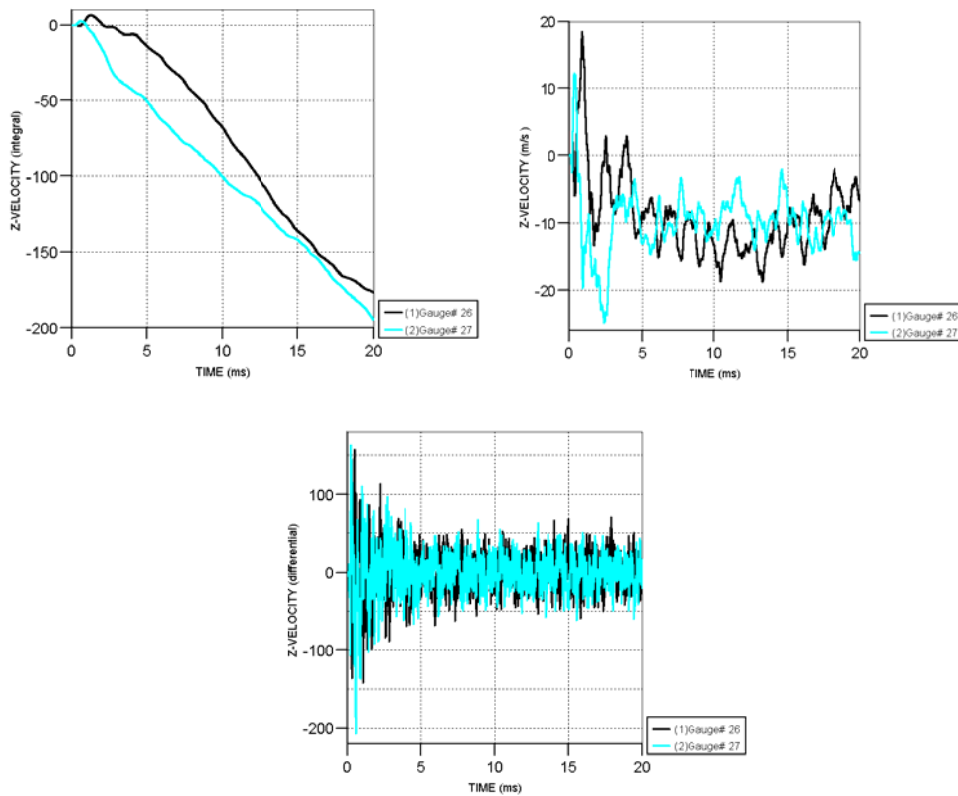
FIGURE 34: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

- Gauges 26 and 27

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.17703 m	18.754 m/s	156.51 m/s ²
Gauge 27	0.19548 m	24.887m/s	206.45 m/s ²

TABLE 17: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

Displacements, velocities and accelerations of gauges 26 and 27 which are in the positions of the accelerometers can be seen in figure 35.



3. With the decrease of the pressure the plate is not plasticized.

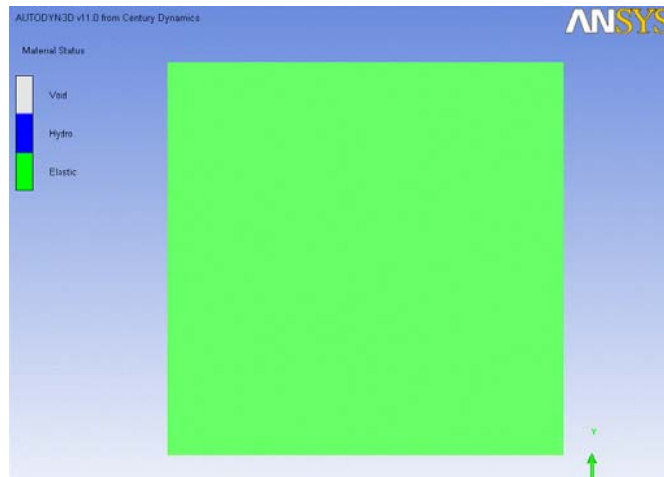


FIGURE 36: BEHAVIOR OF THE PLATE

OBSERVATIONS

1. The displacements, velocities and accelerations are still far from the experimental ones.
2. As the plate is no longer plasticized, in order to increase the peak value of the accelerations the positive phase is going to be decreased.

3.2.1.2.3 MODEL 3

In this case, the positive phase duration is going to be reduced to try to achieve higher accelerations.

	Peak pressure (Pa)	Start time (s)	Peak time (s)	End time (s)
Triangular	77800000	0	0.000025	0.00005

The place where the pressure is going to be applied is the same as before.

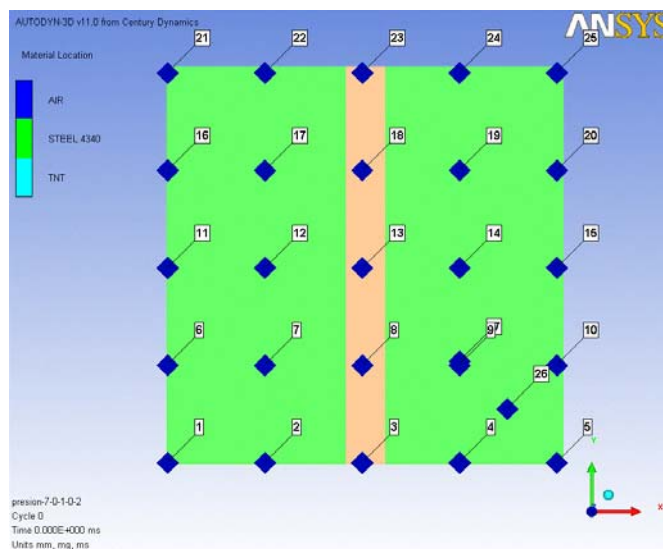


FIGURE 37: ZONE WHERE THE AREA IS APPLIED

RESULTS

1. Displacements, velocities and accelerations:

- Gauges 3, 8, 13, 18 and 23

	Max. displacement	Max. velocity	Max. acceleration
Gauge 3	0.56187 m	23.943 m/s	468.36 m/s ²
Gauge 8	0.52107 m	17.965m/s	260.61 m/s ²
Gauge 13	0.55088 m	28.356 m/s	1078.6 m/s ²
Gauge 18	0.52465 m	17.497 m/s	247.95 m/s ²
Gauge 23	0.54945 m	21.020 m/s	417.83 m/s ²

TABLE 18: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

The graphs below show the displacements, velocities and acceleration of the gauges in the middle of the plate, gauges 3, 8, 13, 18 and 23.

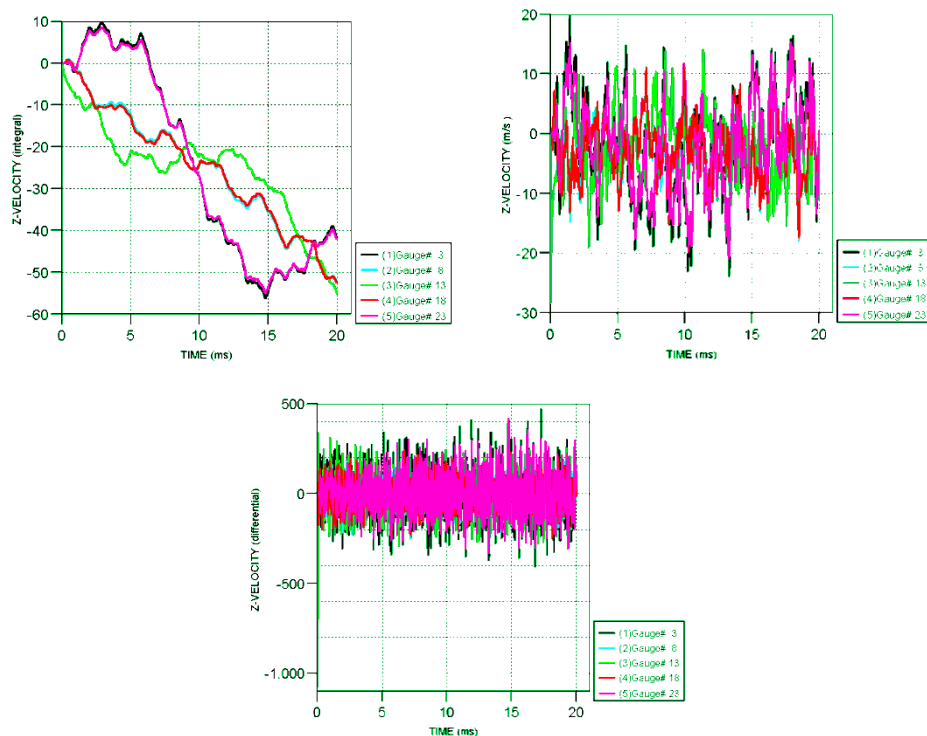


FIGURE 38: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.

- Gauges 26 and 27

	Max. displacement	Max. velocity	Max. acceleration
Gauge 26	0.46839 m	12.253 m/s	225.20 m/s ²
Gauge 27	0.51549 m	13.504 m/s	212.31 m/s ²

TABLE 19: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.

The displacements, velocities and accelerations of gauges 26 and 27 are presented in the figure 39.

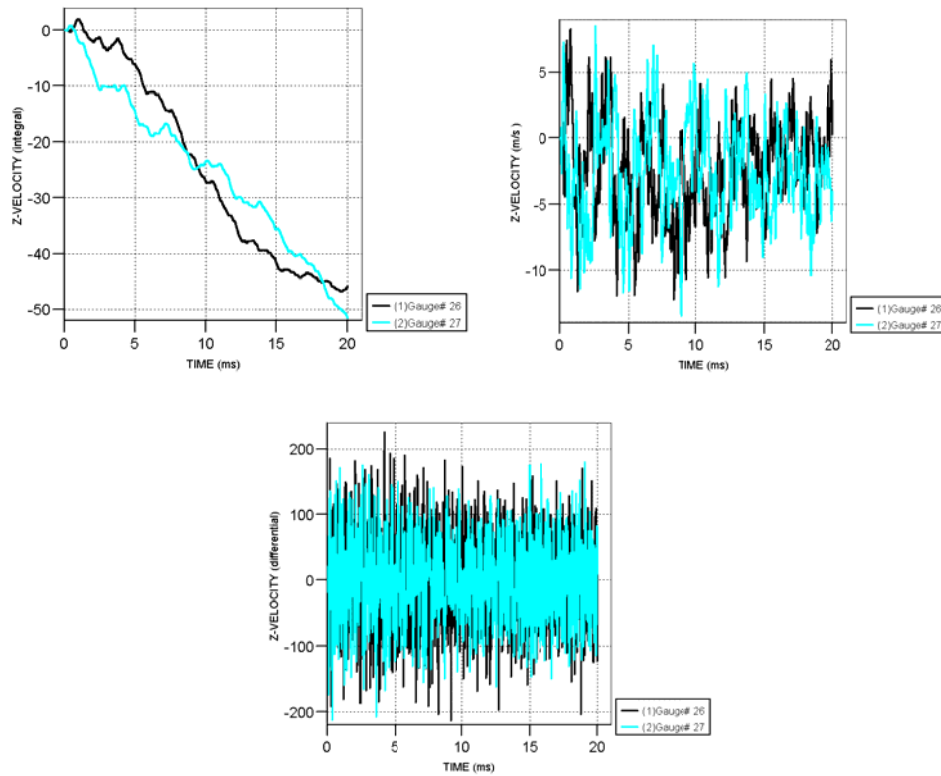


FIGURE 39: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27

2. The plate is not plasticized.

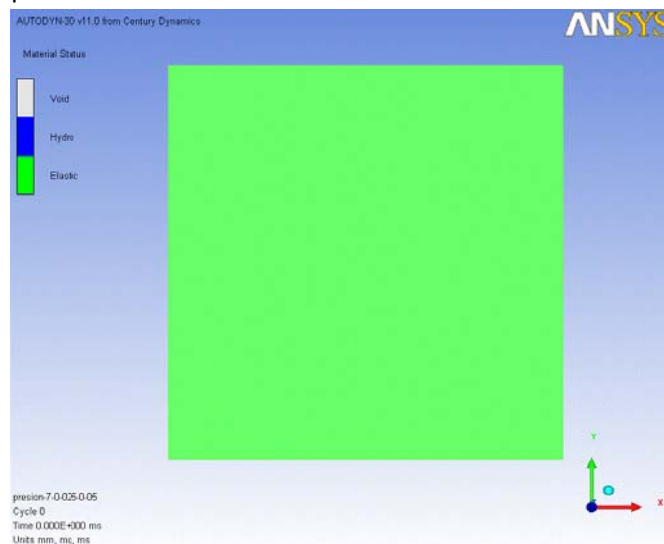


FIGURE 40: BEHAVIOR OF THE PLATE

OBSERVATIONS

1. The displacements, velocities and accelerations are higher than before but still far from the experimental ones.
2. The plate is not plasticized and the accelerations are higher than before. Higher pressures plasticize the plate and shorter positive phase durations increase the value of the accelerations.

3.2.2 SECOND MODELING

The configuration of the plate has been changed in order to:

1. Simplify the problem: The previous tests were done with a complex configuration of the problem. The accelerometers weren't placed on the shock plate itself but on a small plate screwed on it. With the new configuration it is searched to simplify the problem as much as possible to achieve the correct accelerations in the easiest way.
2. Overall view of the accelerations: it is important to know what happens in all the plate not only in two specific points. Considering the pressure distribution as symmetrical, nine accelerometers (the ones shown in the figure below) are placed to have a more realistic view of the accelerations the plate suffers.

In this simplified case there is only one plate of 1mx1mx0.014m of dimensions.

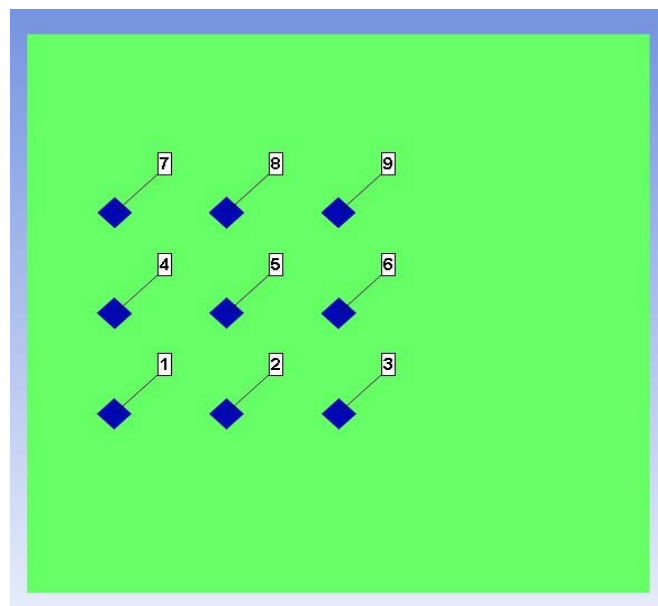


FIGURE 41: POSITIONS OF THE GAUGES

The positions of the gauges are given in table 20, every single position is expressed in m.

	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9
x	0.140	0.320	0.500	0.140	0.320	0.500	0.140	0.320	0.500
y	0.320	0.320	0.320	0.500	0.500	0.500	0.680	0.680	0.680

TABLE 20: POSITIONS OF THE GAUGES

It is important to know that the numeration of the sensors of the experimental test and the one of gauges is not the same.

Numerical	1	2	3	4	5	6	7	8	9
Experimental	3	6	-	2	5	-	1	4	-

TABLE 21: EQUIVALENCE BETWEEN THE NUMERICAL AND EXPERIMENTAL NUMERATION

Using CONWEP it is possible to know the pressure distribution on the plate for 0.02 kg. Once it is known, these pressures can be applied to the model and it is possible to check if the

accelerations achieved are the good ones. All the experimental results presented are reported to the explosion of 0.02 kg of C4.

From now on, only the values of the accelerations are going to be studied since they are the data obtained from the experimental tests.

The pressure is going to be distributed as in the figure below. The plate has been divided in seven different zones to be able to apply the pressures the plate is suffering in a more realistic way than before. The pressure distribution observed in this figure 42 is given by CONWEP for 0.02 kg of C4.

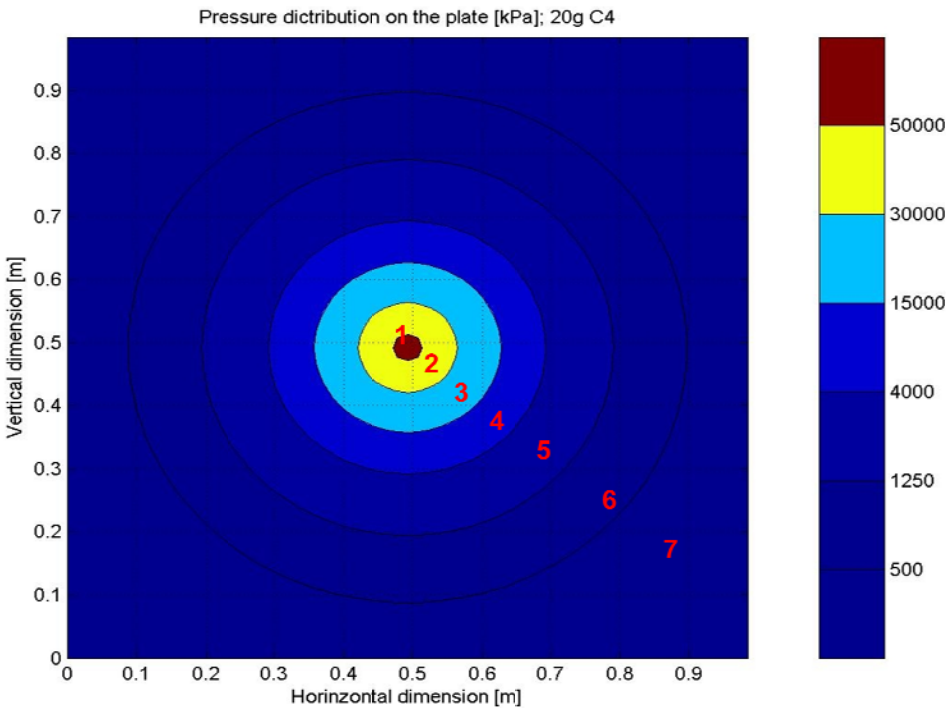


FIGURE 42: PRESSURE DISTRIBUTION

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Diameter (m)	0.040	0.144	0.270	0.404	0.600	0.816	-
Pressure (Pa)	50000000	37500000	22500000	9500000	2625000	875000	500000

TABLE 22: PRESSURE DISTRIBUTION

The table 22 shows the diameter of each zone and the pressure applied in each one. Each zone borders on two different values of pressure, supposing that the pressure decreases in a linear way, the mean of both pressures is applied to each zone.

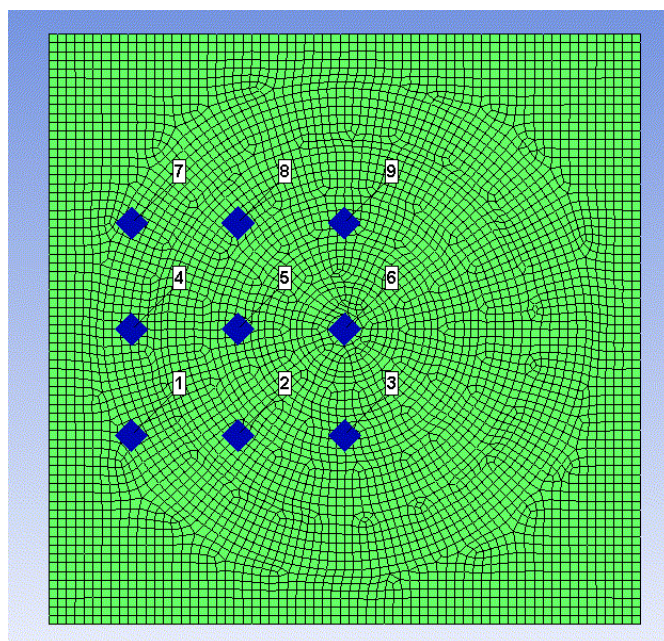


FIGURE 43: PROBES ON THE PLATE

This picture shows in which zone lies each gauge. Because of the resolution of the figure it is a little difficult to see it clearly, the table is presented to solve this problem.

	Zone
Gauge 1	6
Gauge 2	5
Gauge 3	4
Gauge 4	6
Gauge 5	4
Gauge 6	1
Gauge 7	6
Gauge 8	5
Gauge 9	4

TABLE 23: GAUGES AND ZONES

CONWEP gives the positive phase duration for 0.02 Kg of C4. It is important to check if applying the same positive phase durations or the different positive phase durations given by CONWEP the value of the accelerations changes.

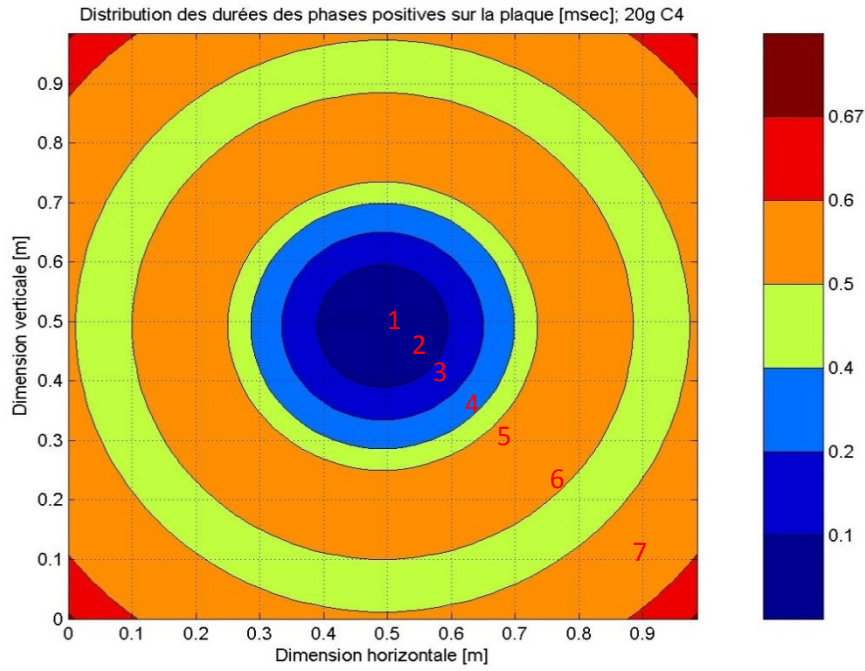


FIGURE 44: POSITIVE PHASE DURATION DISTRIBUTION

3.2.2.1 MODEL 1

All the pressures applied to the plate are going to have the same positive phase duration. The figure 44 shows the positive phase durations on the plate. The zones in which the plate is divided do not correspond to the seven zones used for the pressure. In order to have the same positive phase duration for all the zones, the mean of the durations (taking into account the seven different zones used for pressure) will be used.

	Diameter(m)	Pressure(Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	0.040	50000000	2.5E-4	1.25E-4
Zone 2	0.144	37500000	2.5E-4	1.25E-4
Zone 3	0.270	22500000	2.5E-4	1.25E-4
Zone 4	0.404	9500000	2.5E-4	1.25E-4
Zone 5	0.600	2625000	2.5E-4	1.25E-4
Zone 6	0.816	875000	2.5E-4	1.25E-4
Zone 7	-	500000	2.5E-4	1.25E-4

TABLE 24: DIAMETER, PRESSURE APPLIED, POSITIVE PHASE DURATION FOR EACH ZONE

The plate in this AUTODYN model is going to be divided into cells of 0.015 m of size.

RESULTS

1. The accelerations and profile for 0.02 kg of C4 are presented in the table and figure below.

	Acceleration (m/s ²)
	0.02 kg
Gauge 1	38463
Gauge 2	63988
Gauge 3	110190
Gauge 4	62886
Gauge 5	114430
Gauge 6	378820
Gauge 7	37237
Gauge 8	65352
Gauge 9	114610

TABLE 25: VALUE OF THE ACCELERATIONS

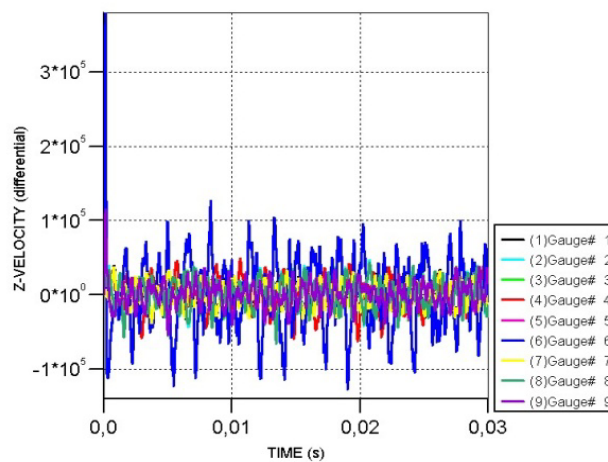


FIGURE 45: PROFILE OF ACCELERATIONS

OBSERVATIONS

1. The value of the accelerations is higher than the experimental one. The value of the acceleration of gauge number 5 is 114430 m/s² while for the experimental result it is close to 30000 m/s². It is not possible to talk about the gauge number 6 (the one with the highest value for the acceleration) because there is not an experimental result to compare with.

3.2.2.2 MODEL 2

In the first model, the one with the same positive phase duration for the different pressures, the values of the accelerations were higher than they should be. Now, it is going to be checked if using different positive phase durations has an influence on the values of the accelerations.

As the zones for the pressures and those for the positive phase durations are not the same it is not possible to apply directly the positive phase duration. An approximation of these durations have been done taken into account all the positive phase durations that are found in the same zone for one specific pressure.

	Δt (s)
Zone 1	0.0001
Zone 2	0.0001
Zone 3	0.0001
Zone 4	0.0002
Zone 5	0.0005
Zone 6	0.0005
Zone 7	0.0005

TABLE 26: POSITIVE PHASE DURATION FOR EACH ZONE

0.015 m will be used as the size of the cells of the plate for this AUTODYN model.

RESULTS

1. The value of the accelerations for this second model is presented in table 27. The figure 47 shows the profile of the accelerations.

	Acceleration (m/s^2)
	0.02 kg
Gauge 1	40206
Gauge 2	76879
Gauge 3	89034
Gauge 4	59870
Gauge 5	92585
Gauge 6	428110
Gauge 7	39818
Gauge 8	69835
Gauge 9	91595

TABLE 27: VALUE OF THE ACCELERATIONS

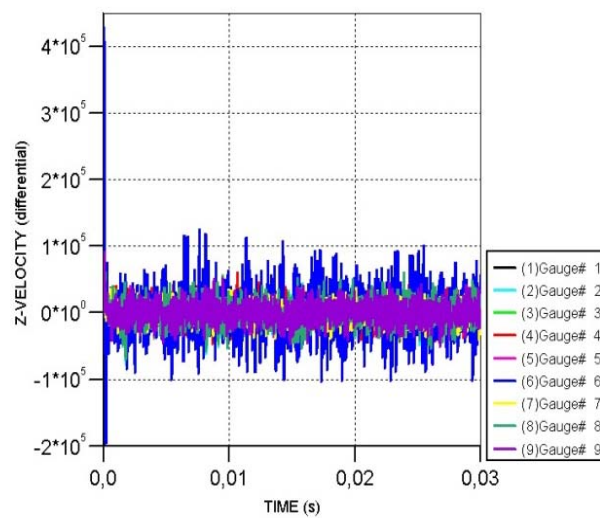


FIGURE 46: PROFILE OF ACCELERATIONS

OBSERVATIONS

1. The acceleration for the gauges 1, 2, 6, 7 and 8 are higher than the values of the previous model.

The values for the experimental test (pink) are much lower than the ones achieved for the 0.02 kg with the same positive phase duration for each zone (blue) and with different positive phase duration (red).

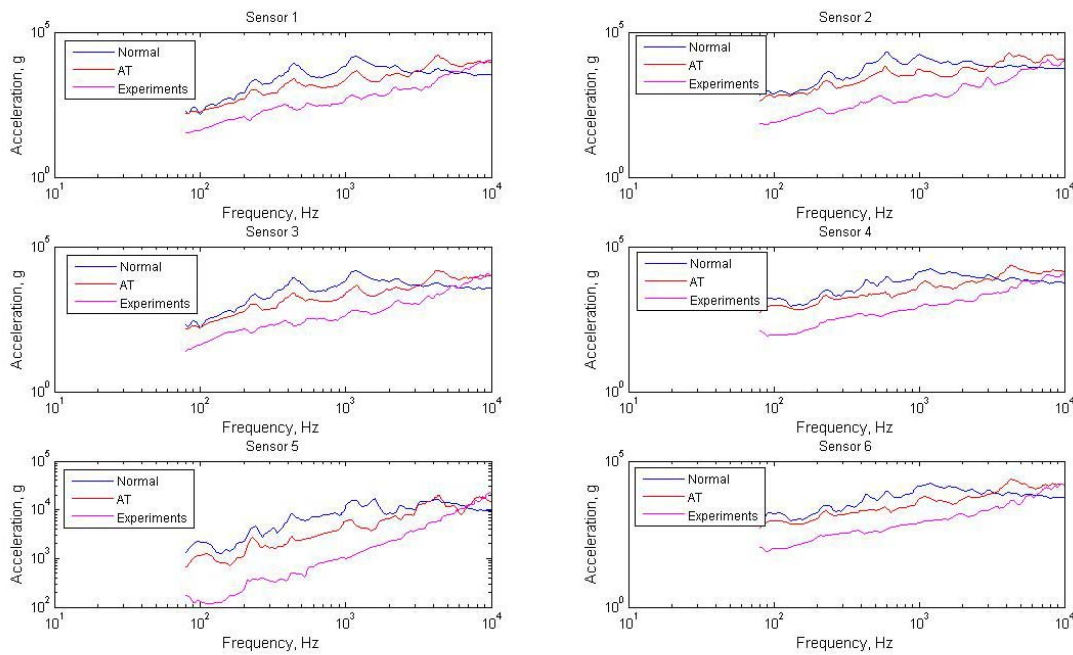


FIGURE 47: SRS FOR 0.02 KG

3.2.2.3 MODEL 3

Model 1 and 2 use the pressure given by CONWEP, but as it is unknown how CONWEP calculates the positive phase duration, this one is going to be calculated through the impulse.

There is one expression which relates the impulse and the positive phase duration. Knowing the impulse of the shock wave and knowing the value of the overpressure, the duration will be:

$$t_0 = \frac{2I}{P}$$

The impulse distribution on the plate for 0.02 kg C4 is presented in figure 49.

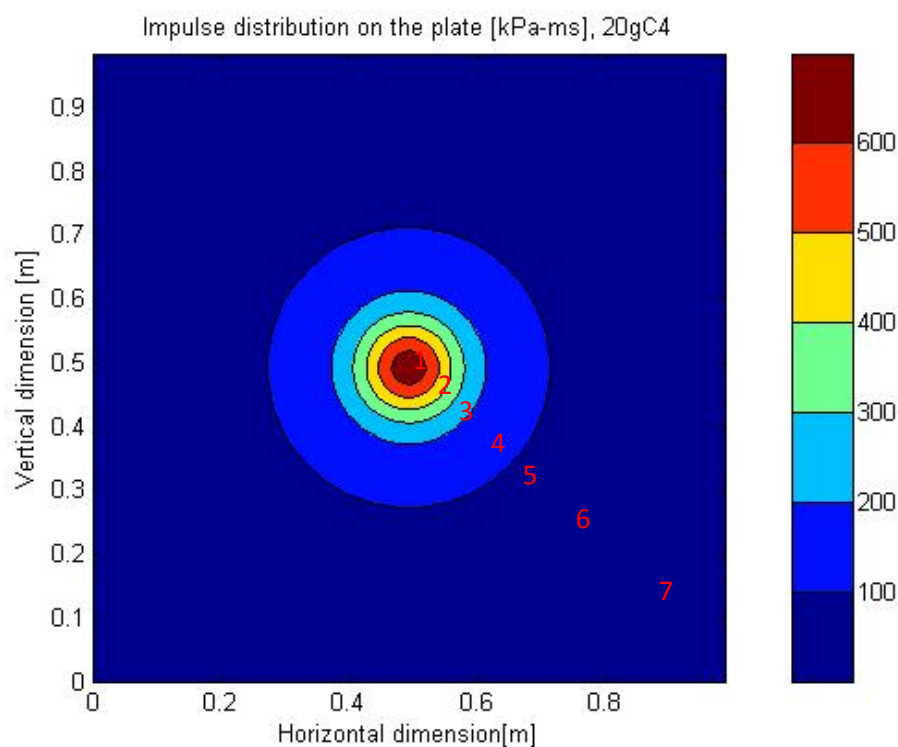


FIGURE 48: IMPULSE DISTRIBUTION

Taking the different zones used and the expression written before into account it is possible to find the positive phase duration for each zone.

	IMPULSE (Pa-s)	PRESSURE (Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	600000	50000000	2,40E-05	1,20E-05
Zone 2	475000	37500000	2,53E-05	1,27E-05
Zone 3	250000	22500000	2,22E-05	1,11E-05
Zone 4	150000	9500000	3,16E-05	1,58E-05
Zone 5	100000	2625000	7,62E-05	3,81E-05
Zone 6	100000	875000	2,29E-04	1,14E-04
Zone 7	100000	500000	4,00E-04	2,00E-04

TABLE 28: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE

The size of the cell of the plate in the AUTODYN model is 0.015 m.

RESULTS

1. The value and the profile of the acceleration for each gauge are shown in table 29 and figure 50.

	Acceleration (m/s ²)
	0.02 kg
Gauge 1	22191
Gauge 2	32151
Gauge 3	104040
Gauge 4	22619
Gauge 5	105370
Gauge 6	452470
Gauge 7	20807
Gauge 8	36758
Gauge 9	104770

TABLE 29: VALUE OF THE ACCELERATIONS

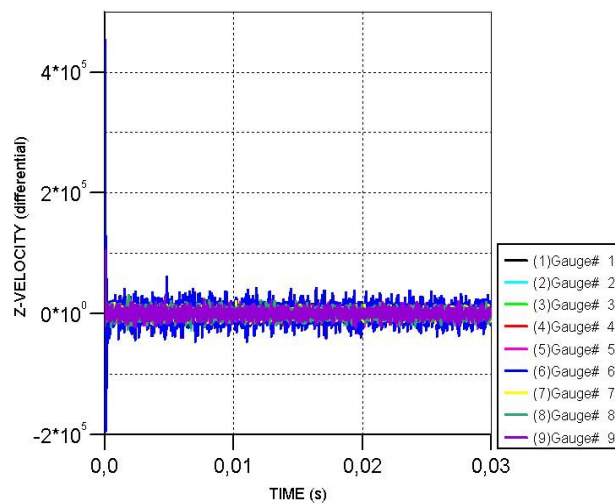


FIGURE 49: PROFILE OF ACCELERATIONS

OBSERVATIONS

1. Most of the values of the accelerations are lower than before. It is important to notice that the positive phase durations calculated through the impulse are more than ten times shorter than the ones given by the CONWEP.

	Acceleration(m/s ²)		
	0.02 kg	0.02 kg _Δt	0.02 kg _impulse
Gauge 1	38463	40206	22191
Gauge 2	63988	76879	32151
Gauge 3	110190	89034	104040
Gauge 4	62886	59870	22619
Gauge 5	114430	92585	105370
Gauge 6	378820	428110	452470
Gauge 7	37237	39818	20807
Gauge 8	65352	69835	36758
Gauge 9	114610	91595	104770

TABLE 30: COMPARISON OF THE ACCELERATIONS FOR 20G

The table shows that the values of the accelerations for this new model are in some cases (gauges 2 and 4) less than the half of the value of model 2 (different positive phase durations given by CONWEP). For gauges 3, 6 and 9 there are not experimental results.

2. The SRS from the experimental results and our SRS is closer than it was before.

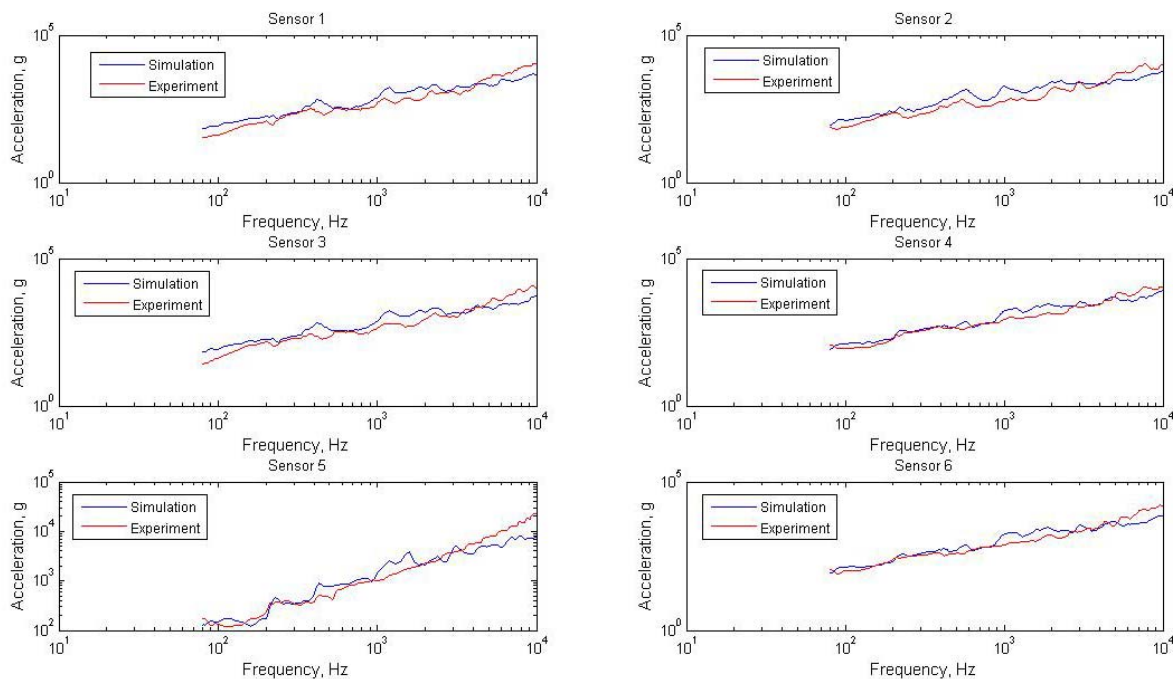


FIGURE 50: SRS FOR 0.02 KG

Experimental	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6
Numerical	Gauge 7	Gauge 4	Gauge 1	Gauge 8	Gauge 5	Gauge 2

TABLE 31: CORRESPONDENCE BETWEEN THE EXPERIMENTAL AND NUMERICAL NUMERATION

All the SRS have been done with the data corresponding to 0.030 seconds of simulation. It is important to know if the duration of the simulations has an influence on the SRS and if so, how this influence is.

To figure out if there is a relationship between the SRS obtained and the duration of the simulation, several SRS with different durations have been done. In the picture below the SRS for 0.003 s, 0.005 s, 0.010 s and 0.030 s are presented.

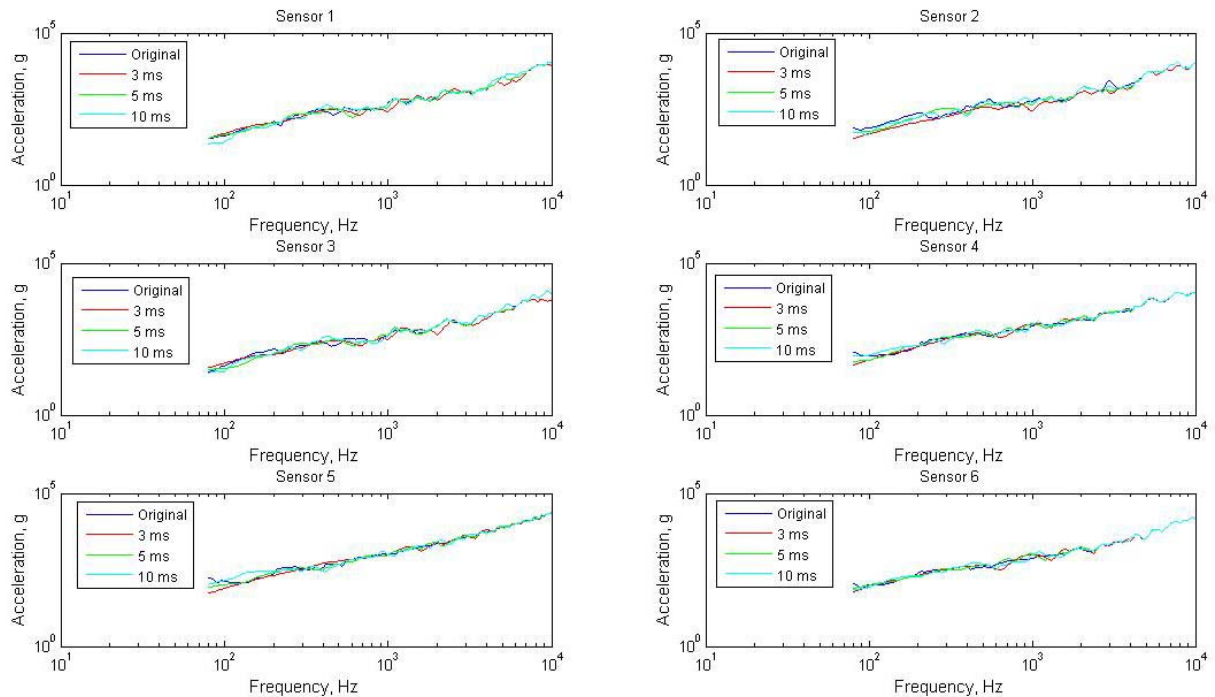


FIGURE 51: SRS FOR DIFFERENT DURATIONS

There is not a big difference between the values of the accelerations reached by the different SRS.

This is a good result because it allows running shorter simulations without losing information. Shorter simulations require less space of memory and they allow the user to get the results faster.

3.2.3 OTHER SIMULATIONS (10G, 30G AND 40G)

The second model will be studied for the accelerations reached by 0.01 kg, 0.03 kg and 0.04 kg of C4 in order to find if there is a relationship between the explosive charge amount and the SRS evolution.

3.2.3.1 MODEL 1

All the simulations that are going to take place refer to the pressures given by CONWEP with the same positive phase duration for all the seven zones used until now.

0.01 KG

The figure below presents the pressure distribution on the plate for 0.01 kg.

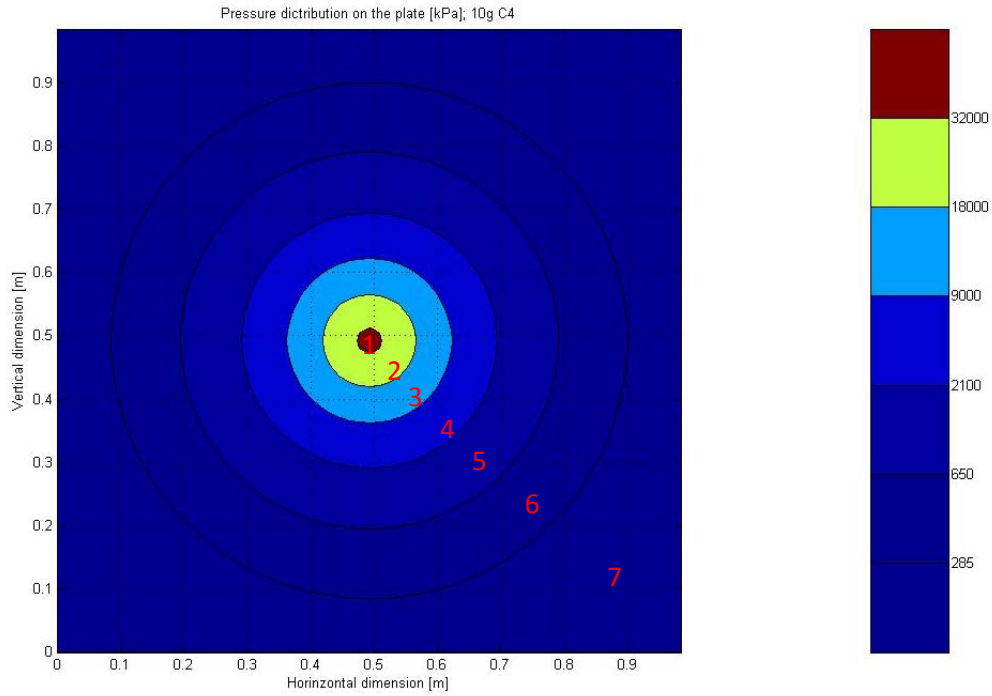


FIGURE 52: PRESSURE DISTRIBUTION FOR 0.01 KG

	Diameter(m)	Pressure(Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	0.040	32000000	2.5E-4	1.25E-4
Zone 2	0.144	25000000	2.5E-4	1.25E-4
Zone 3	0.270	13500000	2.5E-4	1.25E-4
Zone 4	0.404	5550000	2.5E-4	1.25E-4
Zone 5	0.600	1375000	2.5E-4	1.25E-4
Zone 6	0.816	467500	2.5E-4	1.25E-4
Zone 7		285000	2.5E-4	1.25E-4

TABLE 32: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.01 KG)

RESULTS

The accelerations reached for the pressures and positive phase durations mentioned are in table 33.

	Acceleration (m/s^2)
	0.01 kg
Gauge 1	25639
Gauge 2	37733
Gauge 3	65120
Gauge 4	34874
Gauge 5	67670
Gauge 6	248510
Gauge 7	24208
Gauge 8	37547
Gauge 9	68194

TABLE 33: VALUE OF THE ACCELERATIONS

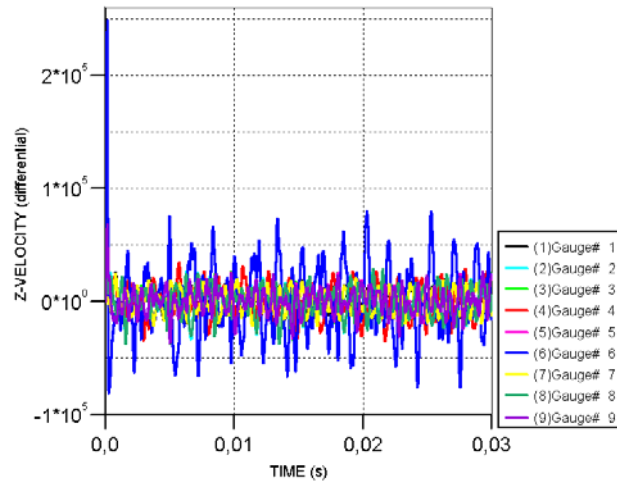


FIGURE 53: PROFILE OF ACCELERATIONS

0.03 KG

The pressure distribution for 0.03 kg of C4 on the plate is shown in the figure below.

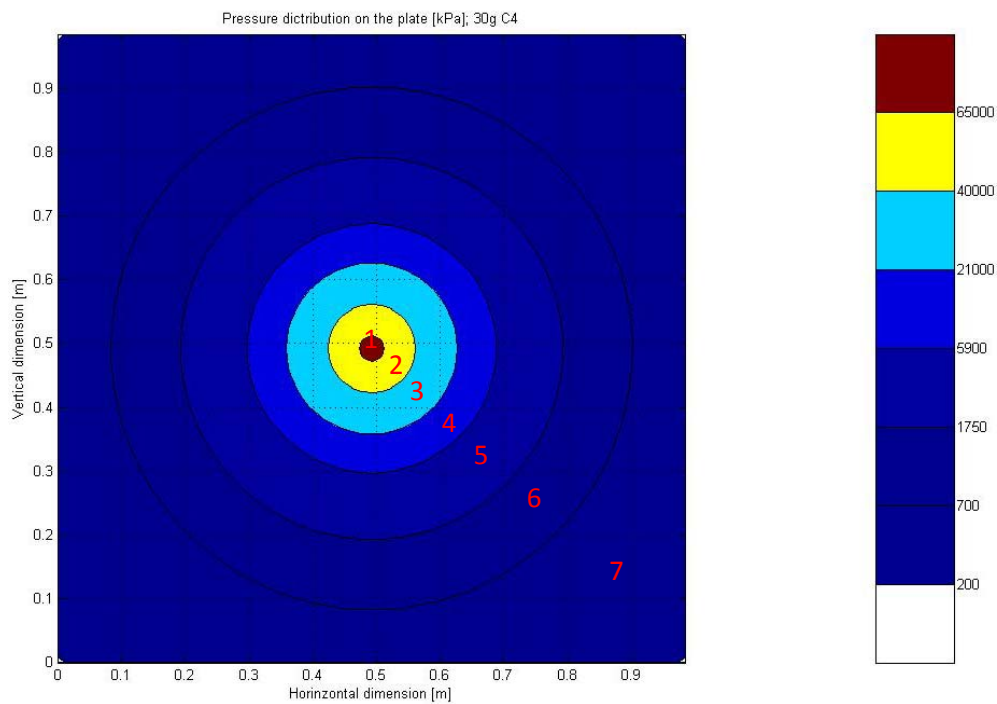


FIGURE 54: PRESSURE DISTRIBUTION FOR 0.03 KG

	Diameter(m)	Pressure(Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	0.040	65000000	2.5E-4	1.25E-4
Zone 2	0.144	52500000	2.5E-4	1.25E-4
Zone 3	0.270	30500000	2.5E-4	1.25E-4
Zone 4	0.404	13450000	2.5E-4	1.25E-4
Zone 5	0.600	3825000	2.5E-4	1.25E-4
Zone 6	0.816	1225000	2.5E-4	1.25E-4
Zone 7		700000	2.5E-4	1.25E-4

TABLE 34: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG)

RESULTS

The value and profile of the accelerations are shown in the table and figure below.

	Acceleration (m/s^2)
	0.03 kg
Gauge 1	56341
Gauge 2	80513
Gauge 3	153660
Gauge 4	78607
Gauge 5	159320
Gauge 6	518760
Gauge 7	57835
Gauge 8	82262
Gauge 9	159890

TABLE 35: VALUE OF THE ACCELERATIONS

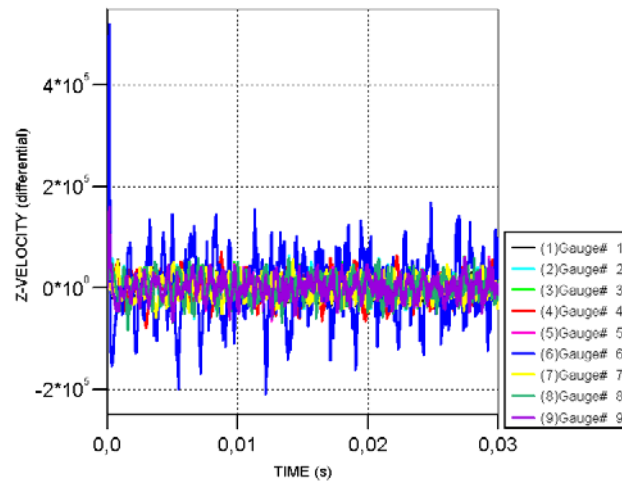


FIGURE 55: PROFILE OF ACCELERATIONS

0.04 KG

For 0.04 kg of C4 the pressure distribution shown in figure 57.

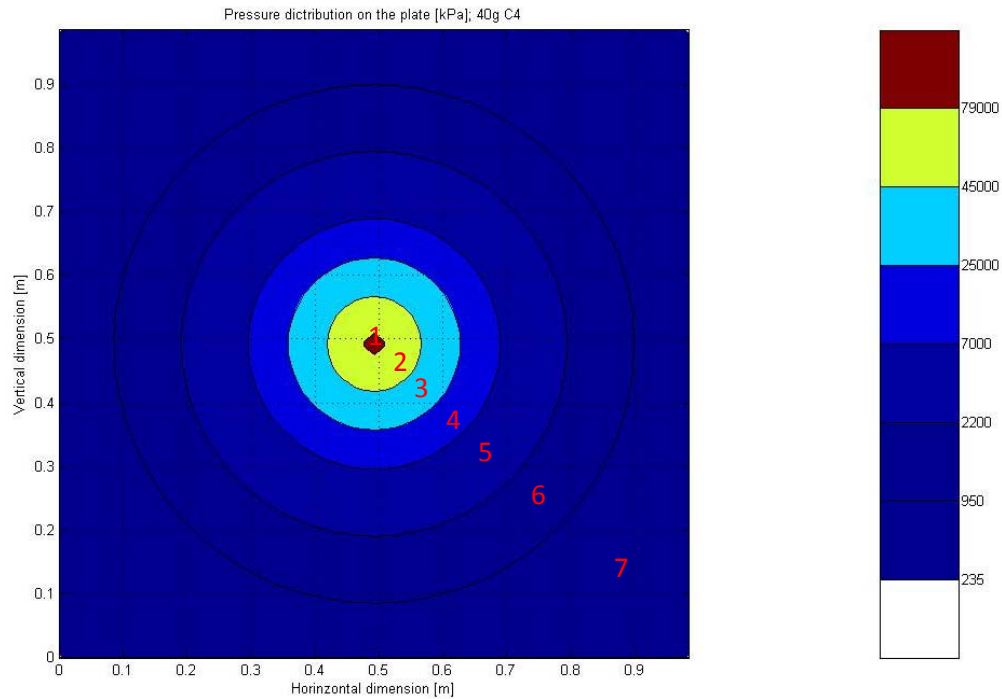


FIGURE 56: PRESSURE DISTRIBUTION FOR 0.04 KG

	Diameter(m)	Pressure(Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	0.040	79000000	2.5E-4	1.25E-4
Zone 2	0.144	62000000	2.5E-4	1.25E-4
Zone 3	0.270	35000000	2.5E-4	1.25E-4
Zone 4	0.404	16000000	2.5E-4	1.25E-4
Zone 5	0.600	4600000	2.5E-4	1.25E-4
Zone 6	0.816	1575000	2.5E-4	1.25E-4
Zone 7		950000	2.5E-4	1.25E-4

TABLE 36: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.04 KG)

RESULTS

The accelerations for 0.04 kg of explosive are the ones in table 37.

	Acceleration (m/s^2)
	0.04 kg
Gauge 1	75864
Gauge 2	100250
Gauge 3	178770
Gauge 4	94994
Gauge 5	185080
Gauge 6	612910
Gauge 7	73527
Gauge 8	103340
Gauge 9	182625

TABLE 37: VALUE OF THE ACCELERATIONS

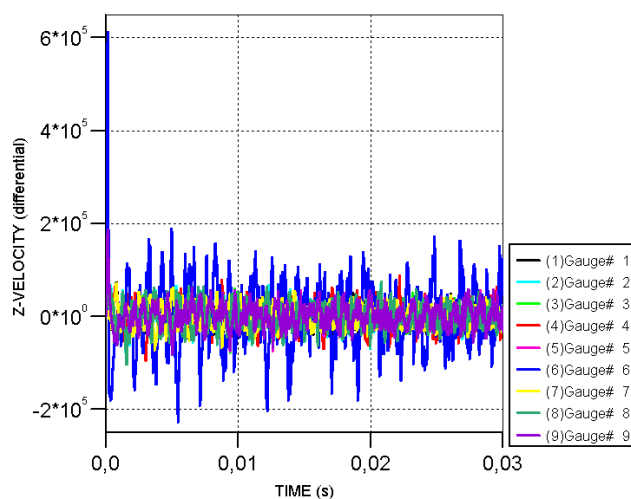


FIGURE 57: PROFILE OF ACCELERATIONS

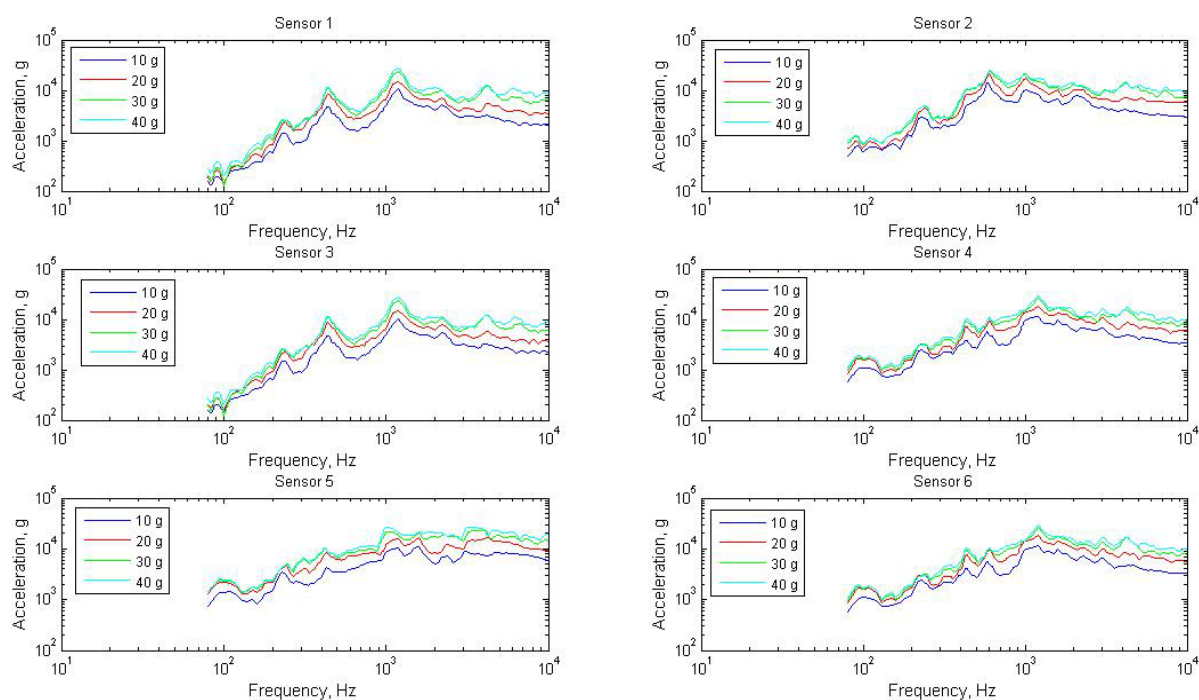


FIGURE 58: SRS FOR 10G, 20G, 30G AND 40G

OBSERVATIONS

1. For 0.01 kg and 0.02 kg the profile of the accelerations is practically the same for all the accelerometers in all the range of frequencies.
2. Between 100 and 250 Hz 0.02 kg, 0.03 kg and 0.04 kg are almost overlapped.
3. For 0.03 kg and 0.04 the profiles of the accelerations are almost overlapped.

3.2.3.2 MODEL 2

In this second model the simulations for the same charges (0.01 kg, 0.03 kg and 0.04 kg) will be done. The pressures will be the ones given by CONWEP while the positive phase duration will be calculated from the impulse.

0.01 KG

In figure 60 the pressure distribution for 0.01 kg is shown.

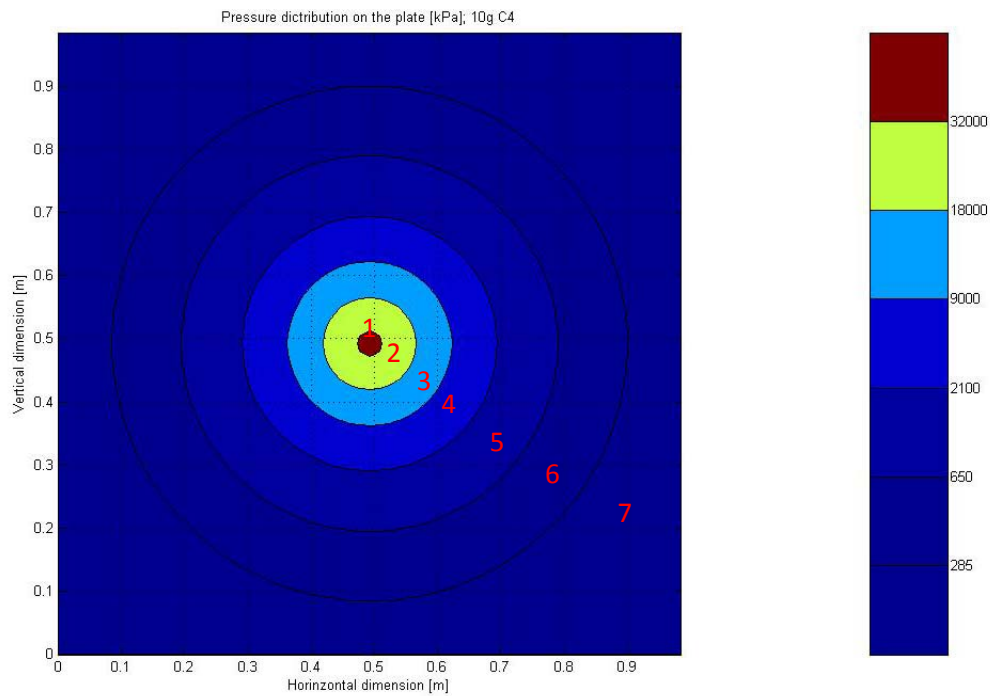


FIGURE 59: PRESSURE DISTRIBUTION FOR 0.01 KG

	IMPULSE (Pa-s)	PRESSURE (Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	350000	32000000	2,19E-05	1,09E-05
Zone 2	300000	25000000	2,40E-05	1,20E-05
Zone 3	187500	13500000	2,78E-05	1,39E-05
Zone 4	100000	5550000	3,60E-05	1,80E-05
Zone 5	62500	1375000	9,09E-05	4,55E-05
Zone 6	50000	467500	2,14E-04	1,07E-04
Zone 7	50000	285000	3,51E-04	1,75E-04

TABLE 38: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.01 KG)

RESULTS

The results of the accelerations for the nine gauges in the plate for 0.01 kg can be seen in the table and figure below.

	Acceleration (m/s ²)
	0.01 kg
Gauge 1	12443
Gauge 2	17811
Gauge 3	63003
Gauge 4	13758
Gauge 5	64640
Gauge 6	289150
Gauge 7	11607
Gauge 8	21316
Gauge 9	63491

TABLE 39: VALUE OF THE ACCELERATIONS

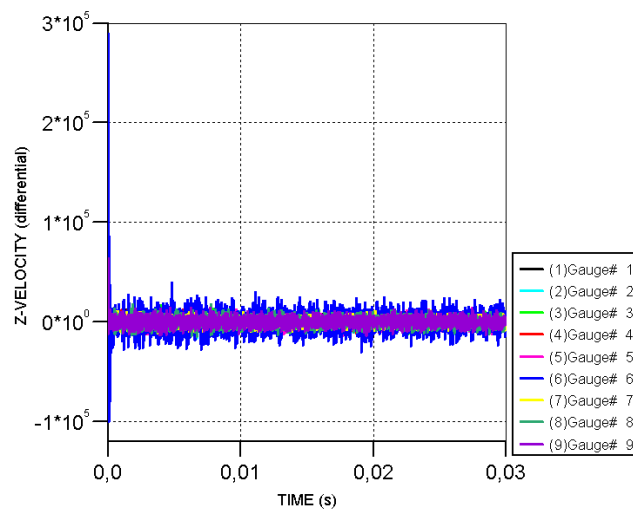


FIGURE 60: PROFILE OF ACCELERATIONS

0.03 KG

The figure 62 shows the pressure distribution on the plate for 0.03 kg of C4

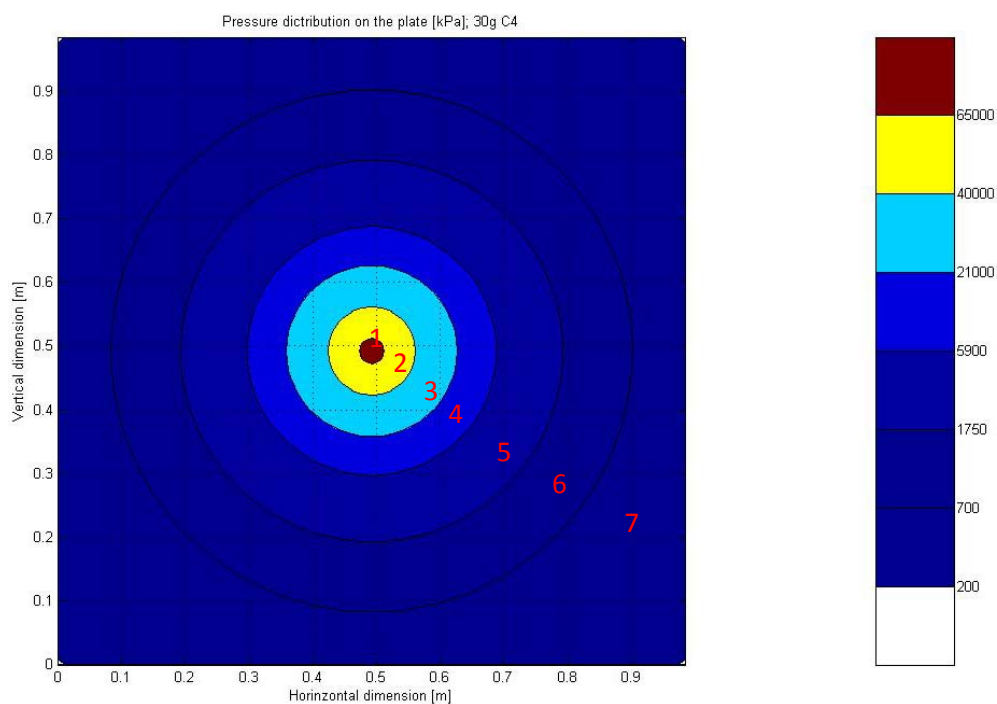


FIGURE 61: PRESSURE DISTRIBUTION FOR 0.03 KG

	IMPULSE (Pa-s)	PRESSURE (Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	900000	65000000	2,77E-05	1,38E-05
Zone 2	750000	52500000	2,86E-05	1,43E-05
Zone 3	425000	30500000	2,79E-05	1,39E-05
Zone 4	200000	13450000	2,97E-05	1,49E-05
Zone 5	125000	3825000	6,54E-05	3,27E-05
Zone 6	100000	1225000	1,63E-04	8,16E-05
Zone 7	100000	700000	2,86E-04	1,43E-04

TABLE 40: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG)

RESULTS

The values for the acceleration and the profile of the accelerations for 0.03 kg of explosive are shown in the table and figure below.

	Acceleration (m/s ²)
	0.03 kg
Gauge 1	29471
Gauge 2	47944
Gauge 3	141120
Gauge 4	303180
Gauge 5	147970
Gauge 6	588050
Gauge 7	248120
Gauge 8	52905
Gauge 9	141820

TABLE 41: VALUE OF THE ACCELERATIONS

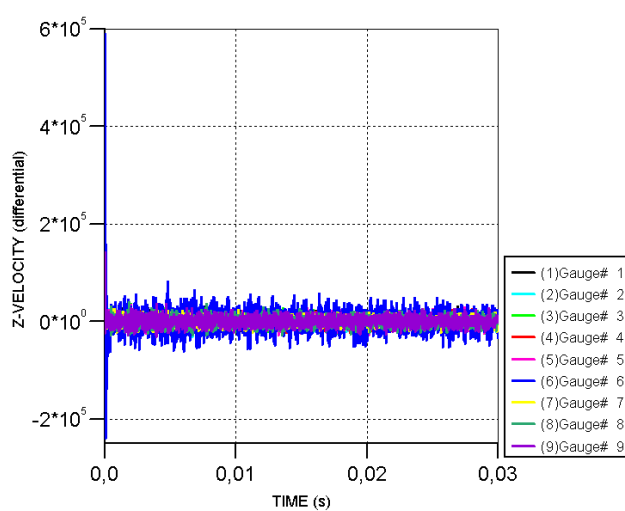


FIGURE 62: PROFILE OF ACCELERATIONS

0.04 KG

The pressure distribution for an amount of 0.04 kg is presented in the figure below.

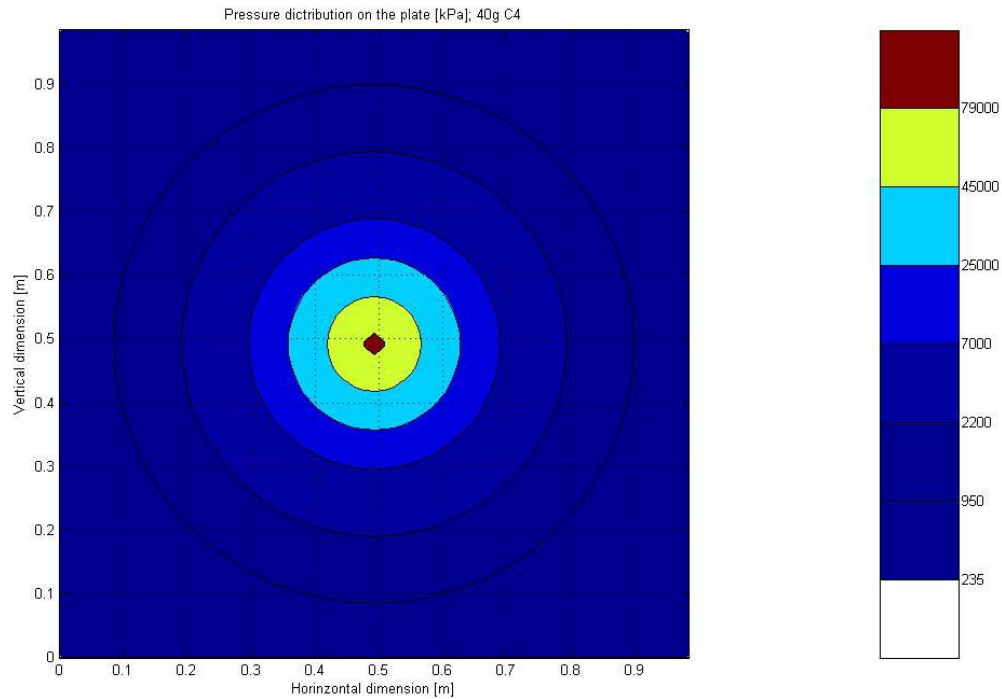


FIGURE 63: PRESSURE DISTRIBUTION FOR 0.04 KG

	IMPULSE (Pa-s)	PRESSURE (Pa)	ΔT (s)	$(\Delta T/2)$ (s)
Zone 1	1100000	79000000	2,78E-05	1,39E-05
Zone 2	850000	62000000	2,74E-05	1,37E-05
Zone 3	425000	35000000	2,43E-05	1,21E-05
Zone 4	200000	16000000	2,50E-05	1,25E-05
Zone 5	125000	4600000	5,43E-05	2,72E-05
Zone 6	100000	1575000	1,27E-04	6,35E-05
Zone 7	100000	950000	2,11E-04	1,05E-04

TABLE 42: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG)

RESULTS

In the table below the accelerations for 0.04 kg of C4 are shown. The figure shows the graph of the accelerations for all the gauges on the plate.

	Acceleration (m/s^2)
	0.04 kg
Gauge 1	40161
Gauge 2	57886
Gauge 3	162500
Gauge 4	437260
Gauge 5	170740
Gauge 6	710750
Gauge 7	35881
Gauge 8	62463
Gauge 9	163260

FIGURE 64: VALUE OF THE ACCELERATIONS

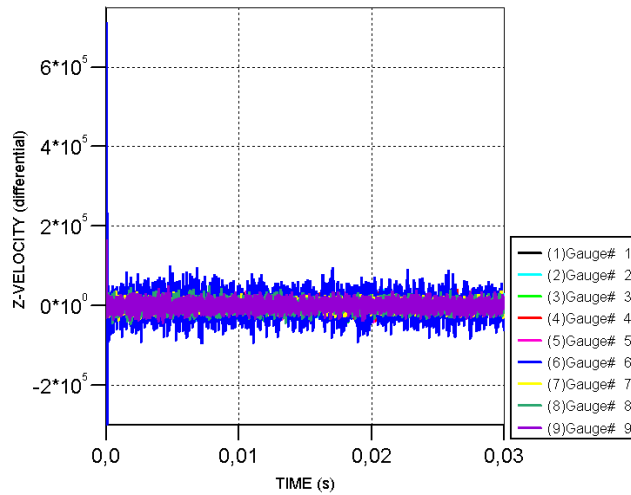


FIGURE 65: PROFILE OF ACCELERATIONS

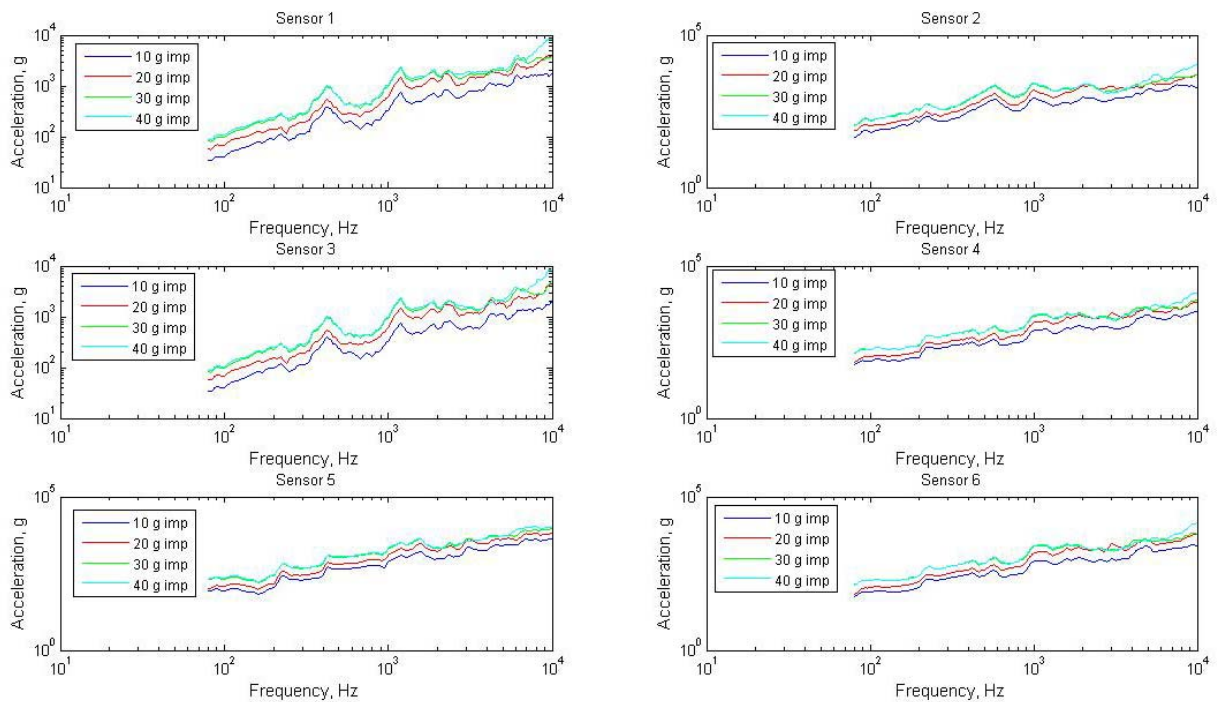


FIGURE 66: SRS FOR 0.01 KG, 0.02 KG, 0.03 KG AND 0.04 KG

OBSERVATIONS:

1. Between 100 and 1000 Hz the profiles for 0.01 kg, 0.02 kg, 0.03 kg and 0.04 kg are parallel. The profile of the accelerations for 0.03 kg and 0.04 kg is almost the same signal.
2. From 1000Hz, 0.02 kg and 0.03 kg are still parallel.
3. From 4000 Hz, 0.03 kg and 0.04 kg are no longer overlapped, they continue their own ways not parallel to 0.01 kg and 0.02 kg.

3.3 NUMERICAL SIMULATION WITH ANSYS

Before achieving the precedent result, many other simulations were studied. The first step was to simulate the same as in AUTODYN but using ANSYS in order to see if AUTODYN wasn't able to achieve good results because of the problem studied (because of the boundary conditions applied).

3.3.1 FIRST MODELING

In first place the geometry of our problem has to be described. It is going to be similar as the one used in previous simulations. The dimensions of the steel plate are: 1mx1mx0.01m.

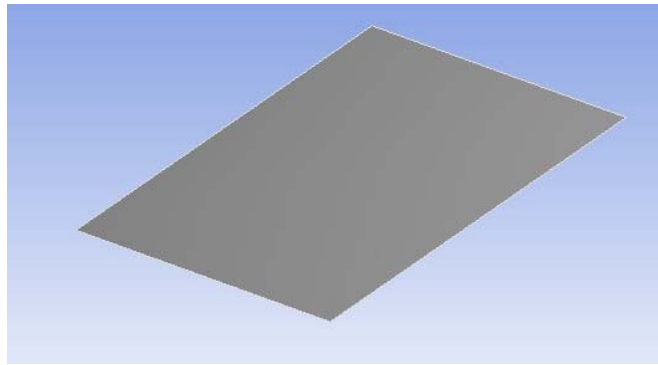


FIGURE 67: GEOMETRY OF THE PROBLEM

Two probes¹ are placed in the two positions where experimentally the accelerometers are. These positions are going to be:

	Accelerometer 1	Accelerometer 2
X (m)	0.740	0.860
Y (m)	0.860	0.140
Z (m)	0.080	0.080

¹ To continue with the nomenclature of Ansys it is used the term “probe” instead of “gauge” (term used in Autodyn)

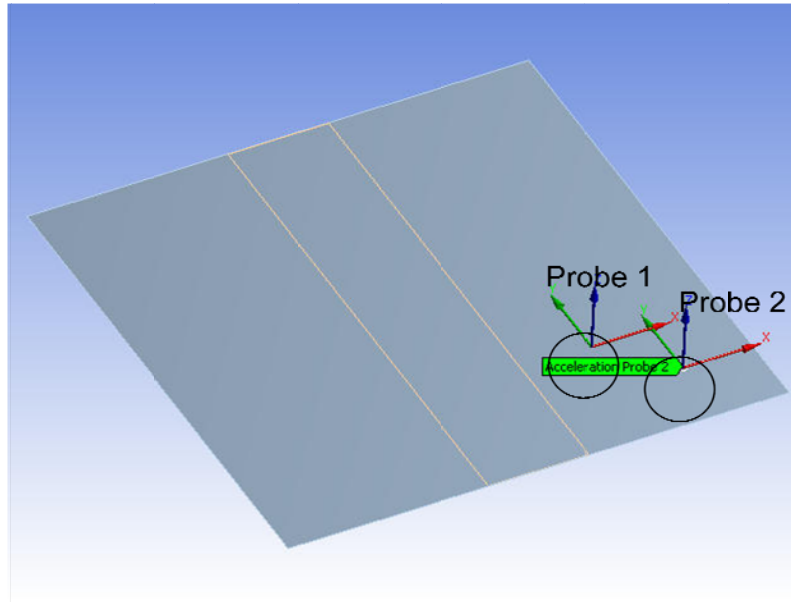


FIGURE 68: POSITION OF THE ACCELERATIONS

In ANSYS is not possible to use the explosives, therefore only models with the pressure as boundary condition will be studied. The values for the pressures are the ones used in the numerical simulations done in AUTODYN (Lagrange-Boundary conditions)

3.3.1.1 MODEL 1

The pressure is applied to the rectangle of 1mx0.2m in the picture.

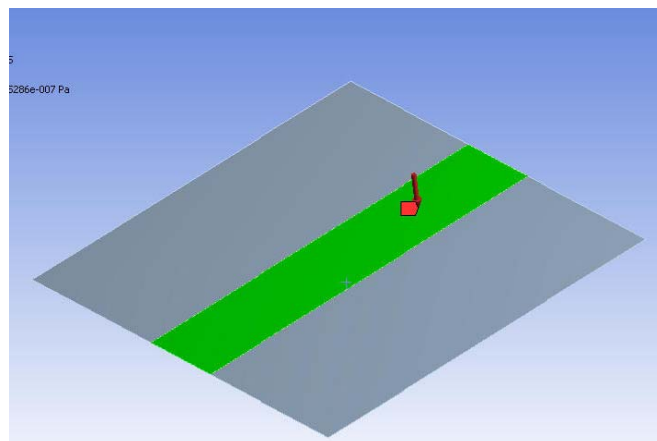


FIGURE 69: ZONE WHERE THE PRESSURE IS APPLIED

The signal introduced is a sinus that will reach its maximum value of 114000000 Pa in 0.0001 seconds. Because of CONWEP it is known that the maximum pressure for one sphere of 0.02 kg is 114000000 Pa. In order to have 0.1kg of explosive, 5 spheres of 0.02 kg are going to be used instead of 3 spheres of 0.033 kg. Due to the short duration of the positive phase duration the sinus signal can be approximated to a triangular signal, the one used for the first modeling in AUTODYN.

If the function is:

$$P = P \cdot \sin(y \cdot \text{time})$$

And the maximum pressure is reached in $\frac{\Delta t}{2} = 0.0001\text{ms}$, y should be:

$$y = \frac{90}{0.0001} = 900000$$

	Peak pressure (Pa)	Start time (s)	Peak time (s)	End time (s)
Sinus	114000000	0	0.0001	0.0002

$$f(t) = 114000000 \cdot \sin(900000 \cdot \text{time})$$

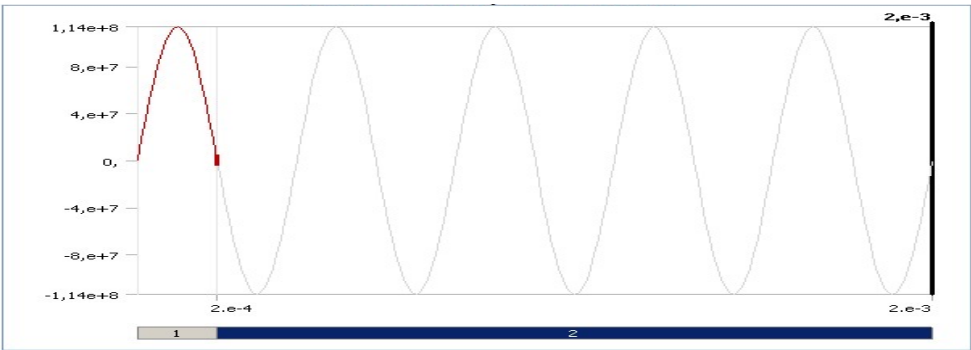


FIGURE 70: PRESSURE APPLIED

RESULTS

	Max. acceleration
Probe 1	330930 m/s ²
Probe 2	418770 m/s ²

TABLE 43: MAXIMUM ACCELERATION FOR PROBE 1 AND PROBE 2

The figures 72 and 73 show the acceleration for the probe 1 and 2, the ones which represent the accelerometers.

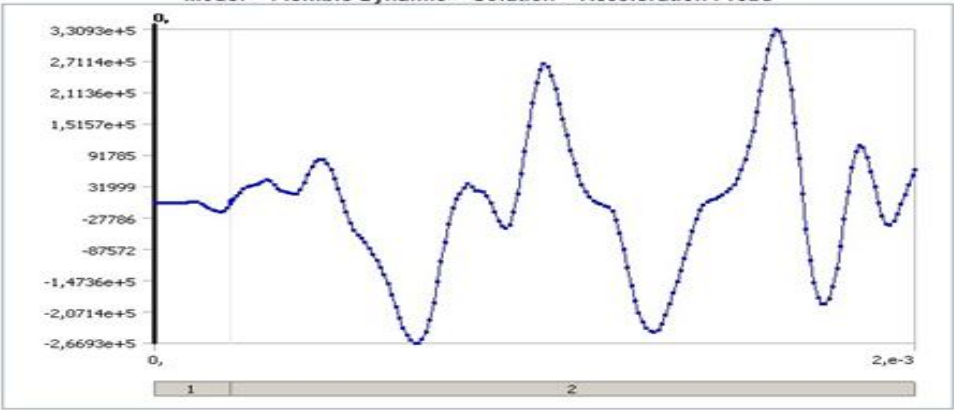


FIGURE 71: ACCELERATION PROBE 1

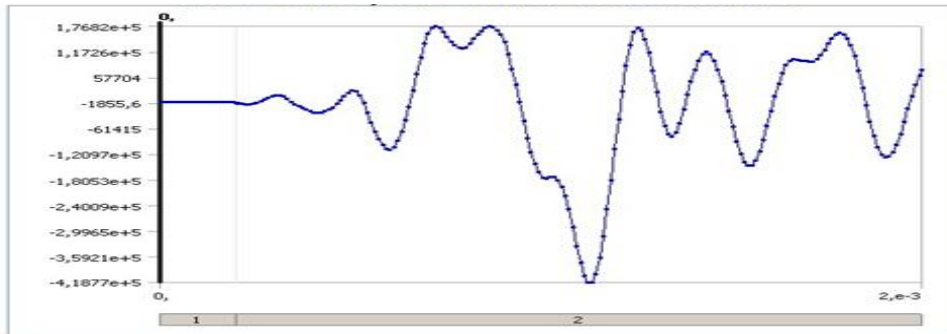


FIGURE 72: ACCELERATION PROBE 2

OBSERVATIONS

1. The values of the accelerations are higher than the experimental ones. For the probe 1 the maximum value of the acceleration is 330930 m/s^2 , almost twenty times the value of the experimental accelerations. For the second probe, the acceleration is 418770 m/s^2 , almost twenty times ten times the value of the experimental result.
2. The final deformation of the plate in z-axis is:

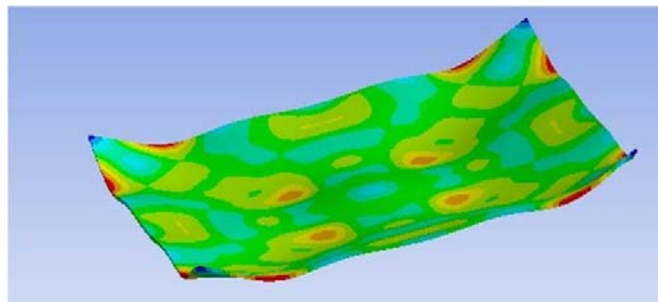


FIGURE 73: DEFORMATION OF THE PLATE DUE TO THE PRESSURE

3. Ansys should keep running more time in order to know the profile of the accelerations.

As with Ansys our maximum number of results by default is 1000, this command has to be introduced in the *Flexible Dynamic* in order to achieve the duration needed:

```

Fini
/config,nres,2500 (to obtain 2500 results)
/solu

```

3.3.1.2 MODEL 2

The pressure is going to be reduced to 77800000 Pa (pressure given by a sphere of 0.01 kg , therefore 5 spheres should be used).

The area where the pressure is going to be applied is the green area in the figure below.

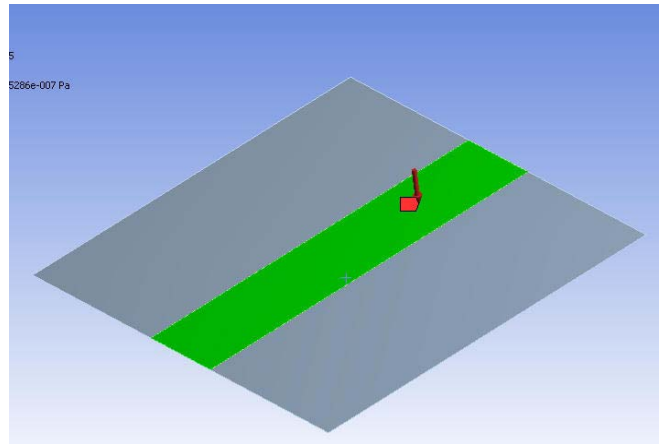


FIGURE 74: AREA WHERE THE PRESSURE IS APPLIED

The signal of the pressure is going to be a sinusoidal with a maximum amplitude of 77800000 Pa.

	Peak pressure (Pa)	Start time (s)	Peak time (s)	End time (s)
Sinus	77800000	0	0.0001	0.0002

$$f(t) = 77800000 \cdot \sin(900000 \cdot \text{time})$$

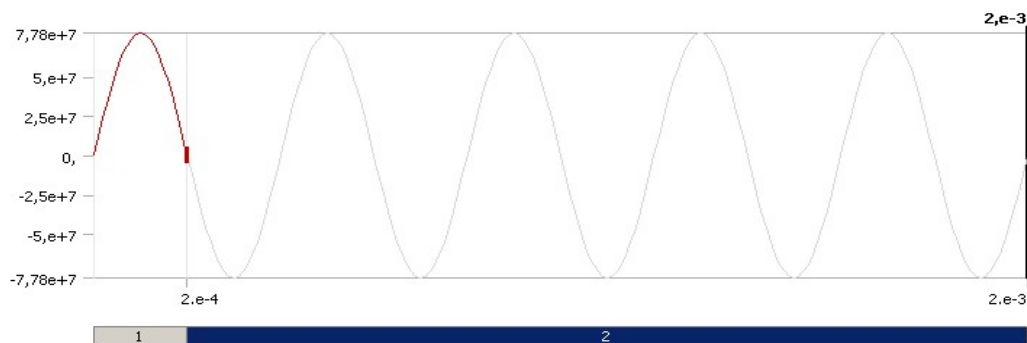


FIGURE 75: SINUSOIDAL PRESSURE

RESULTS

The results for the probe 1 and probe 2 are shown in table 44.

	Max. acceleration
Probe 1	214430 m/s ²
Probe 2	238780 m/s ²

TABLE 44: MAXIMUM ACCELERATION FOR PROBE 1 AND PROBE 2

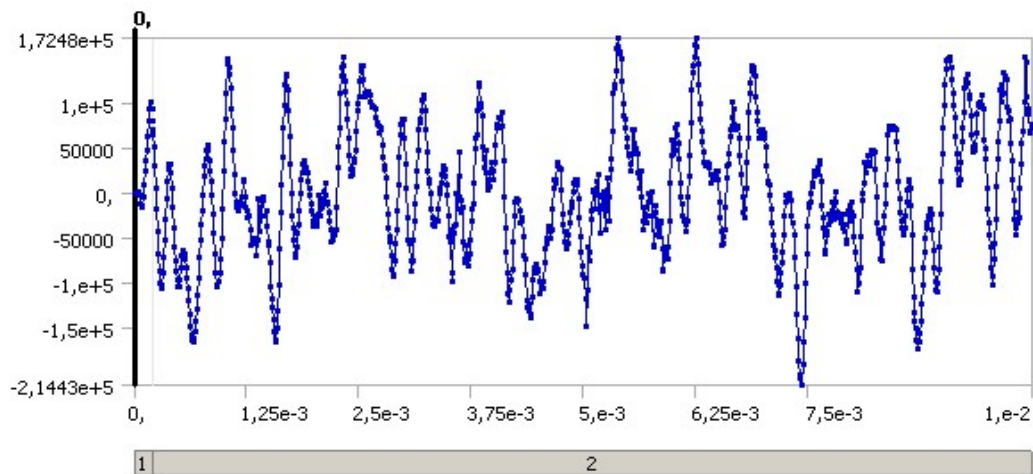


FIGURE 76: ACCELERATION PROBE 1

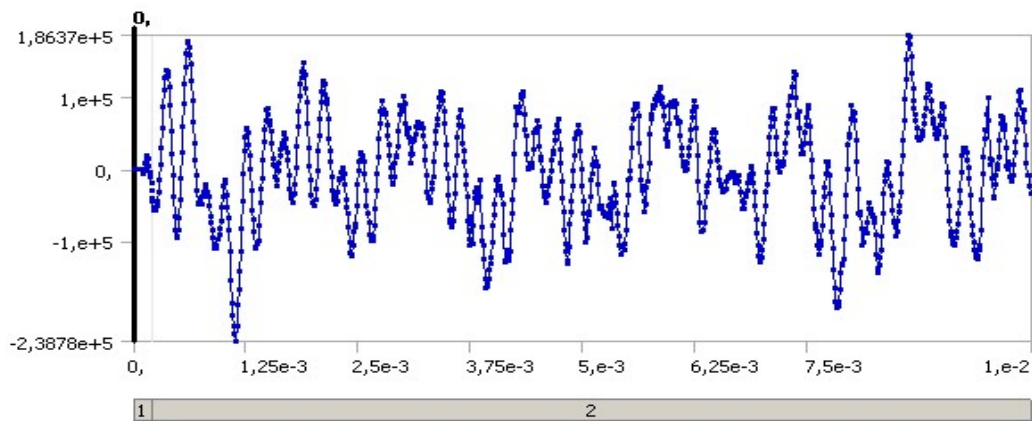


FIGURE 77: ACCELERATION PROBE 2

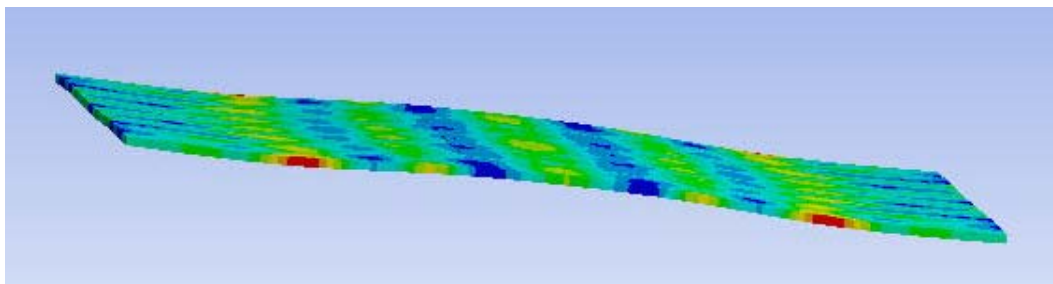


FIGURE 78: DEFORMATION OF THE PLATE

OBSERVATIONS

1. The values are still high, twelve times the experimental values.

3.3.2 SECOND MODELING

As new experimental tests were carried out, a new configuration of the plate was done (See Modeling 2 in AUTODYN). In few words, the configuration has been changed to simplify the problem and the accelerometers are placed in the positions shown in the figure below in order to have a more general vision of the accelerations.

In this simplified case there is only one plate of 1mx1mx0.014m of dimensions.

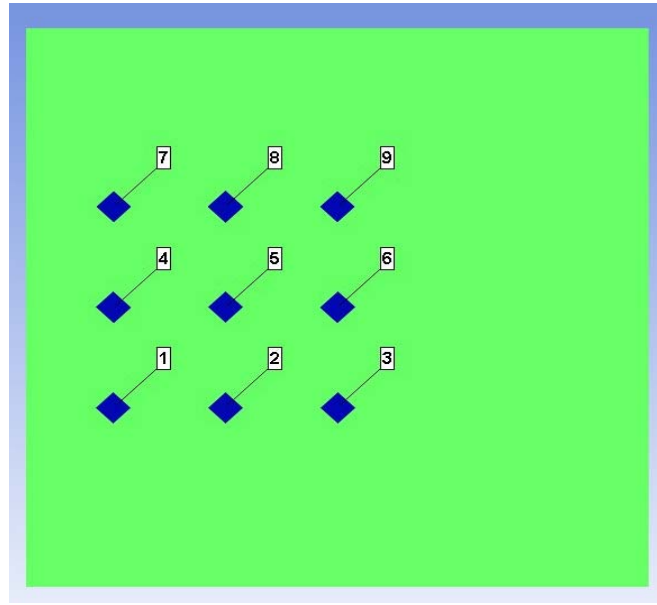


FIGURE 79: POSITION OF THE GAUGES

The positions of the gauges are the following ones, every single position is expressed in m.

	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9
x	0.140	0.320	0.500	0.140	0.320	0.500	0.140	0.320	0.500
y	0.320	0.320	0.320	0.500	0.500	0.500	0.680	0.680	0.680

TABLE 45: POSITION OF THE GAUGES

It is important to remember that the numeration of the experimental test and the numerical simulation is not the same.

Numerical	1	2	3	4	5	6	7	8	9
Experimental	3	6	-	2	5	-	1	4	-

TABLE 46: EQUIVALENCE BETWEEN THE NUMERICAL AND EXPERIMENTAL NUMERATION

3.3.2.1 MODEL 1

Using CONWEP it is possible to know the pressure distribution on the plate for 0.02 kg.

To carry out a flexible dynamic study in ANSYS the time step value for the different pressures applied needs to be same. Due to this reason, the simulations will be done with the mean of the positive phase durations. In this case, 0.00025 s.

The pressure is going to be distributed in the way shown in the figure:

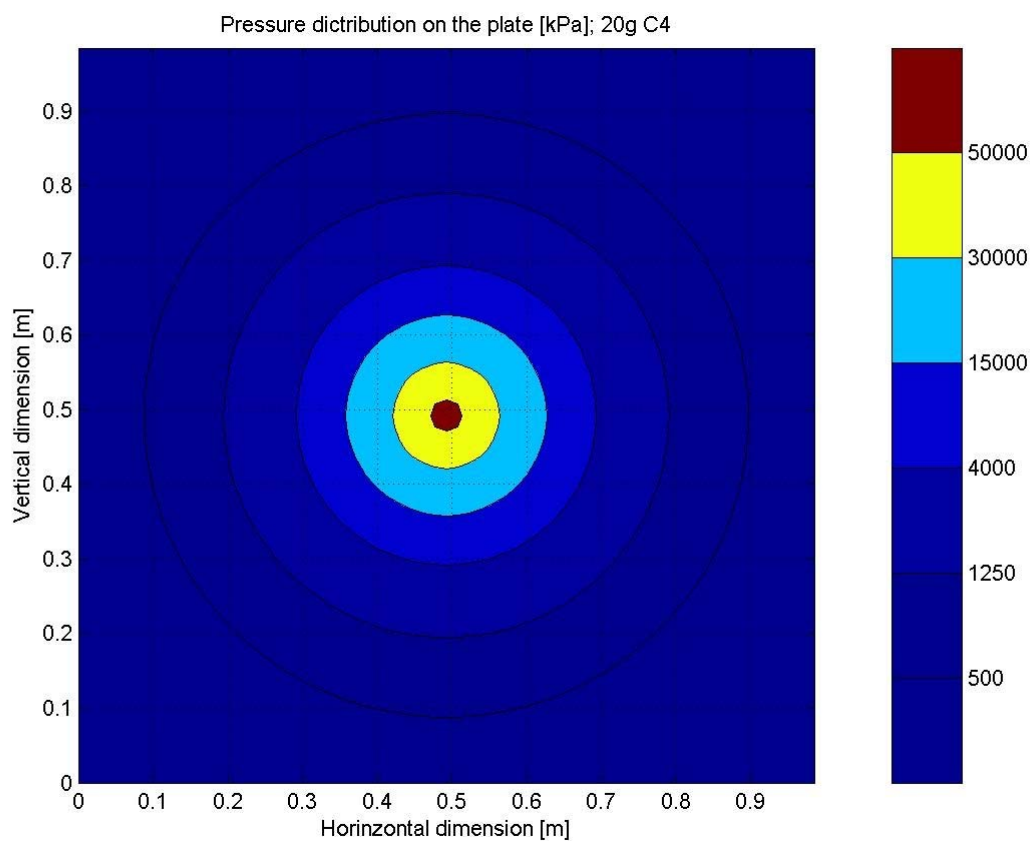


FIGURE 80: PRESSURE DISTRIBUTION

The same pressure distribution as in AUTODYN is used. The dimensions and pressures applied in each zone are reproduced in table 47 to make it easier to understand the next steps.

ZONE	DIAMETER (m)	PRESSURE (Pa)
1	0.040	50000000
2	0.144	37500000
3	0.270	22500000
4	0.404	9500000
5	0.600	2625000
6	0.816	875000
7	-	500000

TABLE 47: ZONES, DIAMETERS AND PRESSURES APPLIED

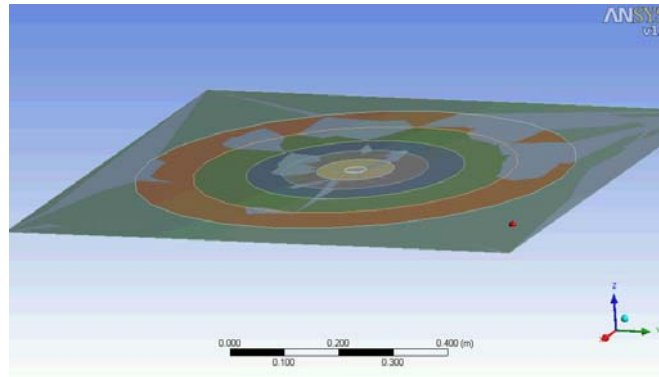


FIGURE 81: MODELISATION OF THE PRESSURE DISTRIBUTION

The pressure is going to be applied as a sinus signal so:

ZONE	PRESSURE (Pa)	START TIME (s)	PEAK TIME (s)	END TIME (s)
1	$50000000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
2	$37500000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
3	$22500000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
4	$9500000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
5	$2625000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
6	$875000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250
7	$500000 \cdot \sin(720000 \cdot \text{time})$	0	0.000125	0.000250

TABLE 48: SIGNAL PRESSURE APPLIED

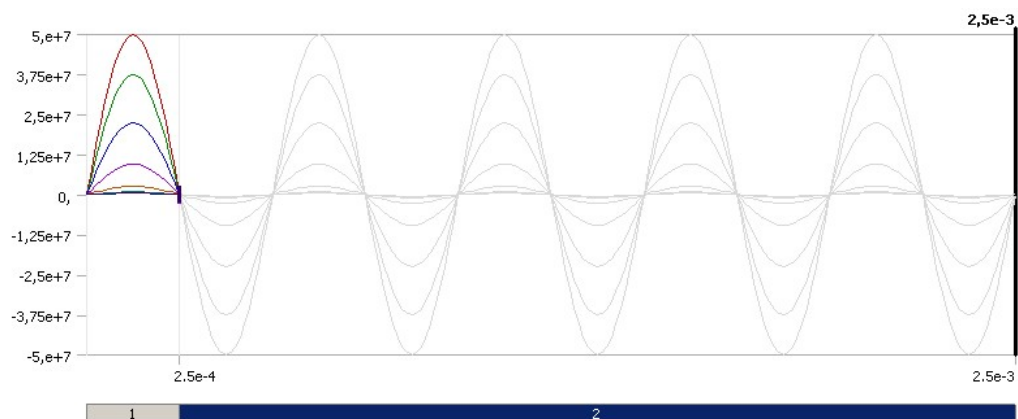


FIGURE 82: PRESSURE PROFILE

As there are several zones with different pressures, connections are going to be needed in order to maintain the surfaces together.

OBSERVATIONS

Due to the many connections in this model, the simulation takes long time. The simulation stops in the second step due to a problem with the convergence.

3.3.2.2 MODEL 2

In order to discover the reason of this problem of convergence the number of connections is reduced. No other boundary condition is applied but the pressure. The problem is called as the “free problem”.

OBSERVATIONS

The speed of the solver is faster than before but there is still the same problem with the convergence, always in the second step.

Instead of placing the gauges on the surface they are going to be placed in the plate. Proceeding this way there won't be problems with the probes lying so close to different surfaces.

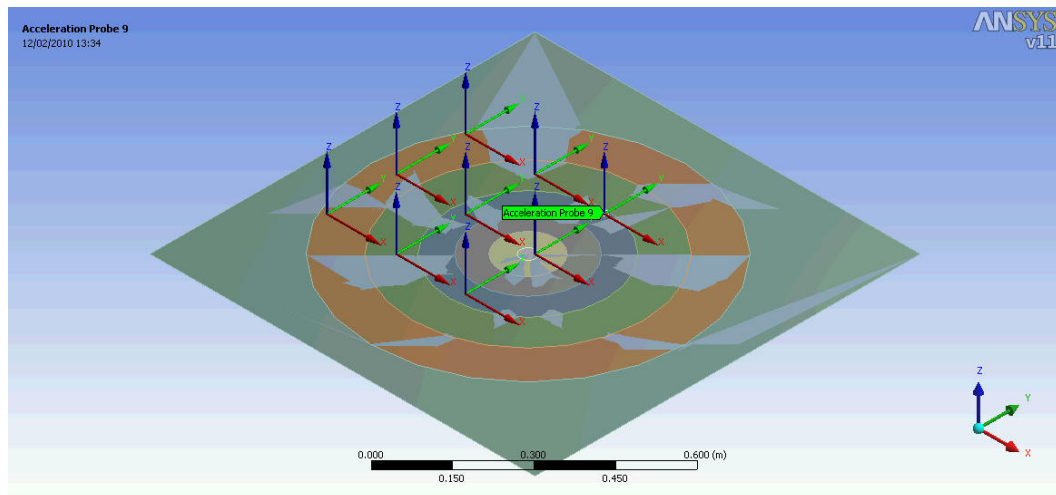


FIGURE 83: GAUGES

3.3.2.3 MODEL 3

Due to the difficulties found when trying to solve the problem as a free problem, simply supported boundary conditions are going to be used in each corner of the plate. The model will not be as realistic as the ones before but it will help us to find out the reason of this convergence problem.

RESULTS

The values of the accelerations for the simply supported problem are shown in table 49.

	Acceleration (m/s ²)
Gauge 1	49891
Gauge 2	75185
Gauge 3	81456
Gauge 4	61197
Gauge 5	81485
Gauge 6	320340
Gauge 7	50096
Gauge 8	75244
Gauge 9	81465

TABLE 49: ACCELERATION OF THE GAUGES

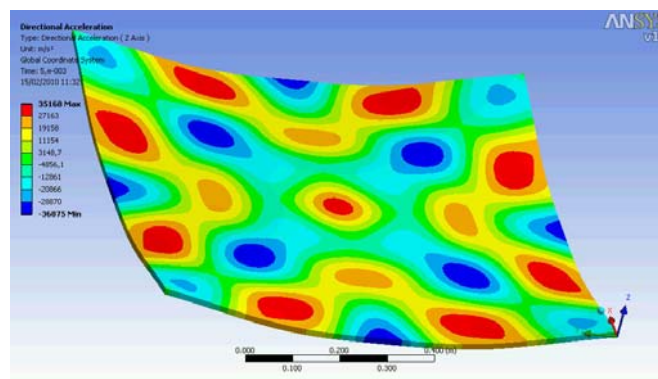


FIGURE 84: ACCELERATION IN Z-AXE OF THE PLATE

OBSERVATIONS

1. ANSYS needs the plate to be attached in, at least, one corner, surface...to be able to solve the problem. There is no way to solve the “free problem” using ANSYS.

3.4 CONCLUSIONS

A good result has been achieved in AUTODYN using the pressure distribution given by CONWEP and calculating the positive phase duration through the impulse given by CONWEP too. Until this moment all the accelerations reached were really far from the experimental results. To achieve the correct values of the accelerations it is essential to impose the correct boundary conditions.

In AUTODYN, at first, the pressure was applied to one zone of the plate but, as this distribution was far from the real pressure distribution, the results weren't correct. When a pressure distribution closer to the reality was applied, the values reached for the accelerations were closer to the experimental results. The correct distribution of the pressure and the positive phase durations calculated through the impulse were the keys to find a model whose results are close to the experimental results.

In ANSYS the main problem is that it is not possible to solve the problem as a free one. ANSYS needs at least one fixed point to be able to solve the problem. Without this point the problem does not converge and it is impossible to have any kind of result. The second problem is that it

is impossible to introduce (in the same dynamic analysis) different positive phase durations for each pressure applied to the plate.

4 CONCLUSIONS

The main objective of this project was to simulate a pyroshock test in order to compare the simulated accelerations with the experimental ones.

Several models were developed and different parameters such as the pressure applied or the duration of the positive phase duration were changed in order to achieve this objective. At first the goal was not reached because the accelerations were very weak or very high and they did not reflect what was happening in reality.

Many other models than the ones presented were studied. Although every new model was an opportunity to learn, just those whose results are more relevant are explained in this report.

There have been two important points in the resolution of the problem. The first one was the pressure distribution while the second one was calculating the positive phase duration with the impulse, both data given by CONWEP. With these two innovations a SRS closer to the SRS of the experimental results than the one we had in first place has been achieved.

The continuation of this project should be focus on:

1. Pressure distribution: seven different zones have been used to solve the problem. It is important to discover the optimum number of zones to divide the plate into, so it will be possible to obtain a SRS closer to the SRS given by the experimental results than the one we have now. It is important to find the equilibrium between the number of zones that will give the correct SRS profile and the computational cost that running the model will cause.
2. Meshing: it is really important to know if the size of the cells used has an influence on the results. If it is the case the model wouldn't be correct. It is indispensable for the model to be mesh insensitive so the results of the accelerations will be similar regardless of the size of the cells.
3. Pressure profile: so far, only triangular profiles have been used to simulate the pressures. It is important to discover which kind of profile is the one more appropriated to simulate the real profile of the pressure.
4. Interaction between plate and structure: The possible interaction of the shock plate and a structure place under it should be studied in order to know if there is some sort of change in the value of the accelerations, their profile...

5 APPENDIX A: EXPLOSIONS

5.1 DEFINITION AND CLASSIFICATION

An explosion is a sudden release of gas at high pressure in the environment. It is sudden because the release must be sufficiently fast for the energy contained in the gas to vanish a shock wave and at high pressure because at the moment of the release, the gas pressure is superior to that of the surrounding atmosphere.

The origin of an explosion is usually classified in:

1. Physical explosion:

In certain cases the high pressure gas is generated by mechanical means or by phenomena without the presence of a fundamental change in the chemical substance. The gas can reach pressure in many different ways: mechanically, gaining heat to gases, liquids or solids or with the overheating of a liquid that can originate an explosion for mechanical means due to the sudden evaporation of itself.

None of these phenomena means change in the chemical substance of the involved substances. The whole process of generation of high pressure, unload and effects of the explosion can be understood in agreement to the fundamental laws of the physics. Some examples of the physical explosions are mechanical explosions, electromagnetic explosions, pneumatic explosions, electrical explosions, nuclear explosions...

2. Chemical explosion:

A chemical explosion happens due to a substance called explosive or because of the chemical reaction between chemical substances that are not explosives themselves. Any chemical reaction can provoke an explosion if gaseous products are emitted, if foreign substances are evaporated or if the temperature of the present gases rises because of the released energy in the reaction.

Chemical explosions are usually subdivided into:

- Explosions in condensed phase (liquid, solid, gas):
 - Thermal explosion
 - Deflagration: subsonic phenomenon where the heat transfer between the reaction zone and the material is on the base of this propagation mechanism. The velocity of the propagation is from cm/s to some tens of m/s.
 - Detonation: supersonic phenomenon (from 1 km/s to 9 km/s). The reaction zone, preceded by a shock front, moves with a constant velocity which is conserved by the energy dispelled.
- Explosions in gas phase (they can be deflagration or detonation)

5.2 TNT EQUIVALENCE

The magnitude of an explosion is measured by the amount of energy released. To be able to compare the effects of the different explosives, a standard which compares the energy released by an explosive with the amount of TNT necessary to release that same amount of energy is used.

An explosion of TNT generates 4520 J/g or kJ/Kg, depending on the magnitude of the explosion.

EXPLOSIVE	kJ/kg	TNT EQUIVALENCE
TNT	4520	1,00
PETN	5800	1,28
TETRYL (CE)	4520	1,00
PICRIC ACID	4180	0,93
EXOGENOUS	5360	1,19
AMATOL	2650	0,59
PENTOLITE	5110	1,13
HEXOLITE	5190	1,15

TABLE 50: TNT EQUIVALENTS

5.3 PHENOMENOLOGY OF AN EXPLOSION

An explosion releases energy in an extreme manner, usually with the generation of high temperatures in a short period of time. There are three aspects:

5.3.1 GAS EXPLOSION

The violent release of the energy transforms the explosive in a high pressure and high temperature gas. This expansion involves the formation of a shock wave which will cause a pressure wave in first place and then will constitute a front of discontinuity called shock front. Each one of the infinitesimal components of the pressure wave moves outwards at its own velocity.

$$a = \sqrt{\gamma RT}$$

a : velocity of the components

γ : isentropic coefficient

R: constant of the perfect gases (287 J/kgK)

T: Temperature (K)

The superior particles of the wave have a higher temperature and are faster than the inferior particles. Because of the difference between their velocities, the inferior ones will be caught by the superior particles.

The front of the wave is more and more pronounced while the queue of the wave presents the opposite phenomenon. From one certain moment, the inertial forces cause the overexpansion of the gas and, consequently, the birth of a depression near the centre of the explosion.

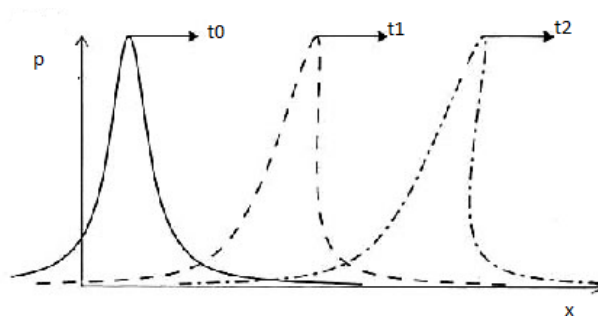


FIGURE 85 FORMATION OF A DISCONTINUITY FRONT

There are two different phases, one positive phase and one negative phase. Of course the pressure of the negative phase can't be under the absolute value of the atmosphere pressure.

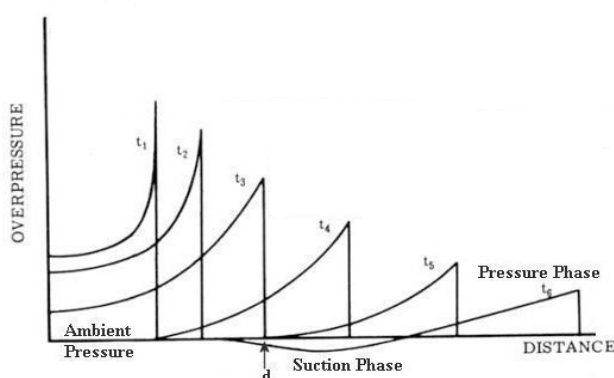


FIGURE 86: PRESSURE DEPENDING ON THE DISTANCE TO THE CENTER OF THE EXPLOSION

One of the characteristics of a high pressure and high temperature gas is the formation of a shock wave which is characterized by an incredible growth of the pressure. This shock wave spreads at a supersonic velocity into the atmosphere. The velocity and the growth of the pressure decrease as the wave continues its way and finally it becomes a sound wave.

The shock wave is followed, in first place, by an air displacement in the direction of the shock wave and later this air displacement will move in the direction to the center of the explosion in the negative phase.

5.3.2 THERMAL RADIATION

The effects are only important in nuclear explosions.

5.3.3 FRAGMENTATION

The fragments are projected with high velocities. This can be very important for those projectiles whose wrapping breaks up. At the time of the impact the fragments lose their kinetic energy and provoke dynamic effects to the structures.

5.4 REPRESENTATION OF THE SHOCK WAVE

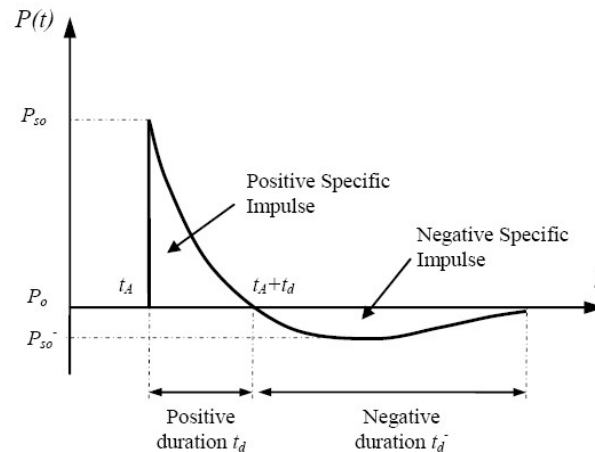


FIGURE 87: REPRESENTATION OF THE SHOCK WAVE

t_A : arrival time

P_{so} : over pressure

P_0 : ambient pressure

P_{so-} : under pressure

T_d : positive duration

T_d^- : negative duration

t_A seconds after the explosion, the pressure reaches a high peak of overpressure. An object situated in this position suffers a lateral and instantaneous strength equal to the product of the overpressure and the projected area of the wave. The peak of overpressure is not a stable condition and the overpressure starts to fall immediately.

Three independent characteristics are required for the waves to be completely described:

1. Initial shock intensity: specified by the peak overpressure, Mach number or particles velocity.
2. Duration.
3. Impulse (force-time product) per unit area for the pressure forces.

Throughout the pressure-time profile, two main phases can be observed; portion above ambient is called positive phase of duration t_d , while that below ambient is called negative phase of duration, t_d^- . The negative phase has a longer duration and lower intensity than the positive phase.

The duration of the shock wave is one of the aspects to cause damage, but it also depends on the strength applied.

Because the positive phase is more damaging than the negative one and because it can be measured in a more precisely way, the positive phase duration is used as an index of the whole duration of the shock wave, although the negative phase is usually twice the duration of the positive.

Related with the duration of the shock wave is the physical distance over which a pressure phase extends. By analogy to simple waves, the positive phase distance is taken as a half of the shock wave.

5.5 REFLECTION OF A SHOCK WAVE

A shock wave is a front of discontinuity which moves with a supersonic velocity in the fluid. It is characterized by a sudden change of velocity, pressure, temperature and specific mass of the fluid.

The shock wave reflects itself when it runs into an obstacle. This reflection can be:

1. Normal reflection: reflection of a wave with zero angle of incidence.
2. Oblique reflection: the shock wave impinges an unyielding surface with one particular angle.
3. Mach stem: the angle of incidence of the wave exceeds a certain angle. It is an interaction of the incident wave and the reflection with the floor.

6 APPENDIX B: PYROSHOCK TESTING

6.1 DEFINITION AND CHARACTERISTICS

Pyrotechnic shock or pyroshock is the transient response of structural elements, components, assemblies, subsystems and/or systems to loading induced by the activation of pyrotechnic (explosive- or propellant-activated) devices incorporated into or attached to the structure.

A pyroshock test is usually designed to simulate:

1. High-frequency (more than 1kHz)
2. Peaks of accelerations from hundreds to thousands of g ($g=9.81\text{m/s}^2$)
3. Durations between 10 and 30 ms

a product may experience as the result of an explosive event such as the separation of the booster rockets on the space shuttle or an explosive impact on a military tank structure.

Pyroshock differs from other types of mechanical shock because there is very little rigid body motion of the product in response to the pyroshock. The pyroshock acceleration time-history measured on the structure is oscillatory and approximates a combination of decayed sinusoidal accelerations with very short duration in comparison to common mechanical shock.

6.2 PYROSHOCK ENVIRONMENTAL CATEGORIES

The pyroshock environment has been divided into the following three categories, depending on the shock severity and frequency range:

1. Near-field: dominated by a direct wave propagation from the source, causing peak accelerations in excess of 5000 g and substantial spectral content above 100 kHz.
2. Mid-field: characterized by a combination of waves propagation and structural resonances, causing peak accelerations between 1000 and 5000 g and substantial spectral content above 10 kHz.
3. Far-field: dominated by structural resonances, with peak accelerations below 1000 g and most of the spectral content below 10 kHz.

For the near-field, only pyrotechnic devices should be used. For the mid-field, either mechanical impact or pyrotechnic devices should be used. For the far-field, electrodynamic shakers, impact or pyrotechnic devices may be used.

6.3 DEFINITION OF THE BEHAVIOR OF A DYNAMIC SYSTEM

The ideal thing to do would be to test the model with the real solicitations it is going to be subjected to. In almost every case it is not possible to do because of the variability and complexity of the solicitations. The conditions for the test should be universal, easy to do (and to reproduce) and representative for the dynamic behavior of the system.

1. Response to a harmonic excitation: harmonic strengths are easy to reproduce and to study theoretically.

2. Response to an impulse, step or ramp function: they are the simplest functions and they are easy to reproduce in a laboratory.

The method used on the tests will depend on many factors: level of acceleration, frequency, required displacement...

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8 INDEX OF FIGURES

FIGURE 1: EXAMPLE OF SRS	4
FIGURE 2: FIRST SETUP.....	6
FIGURE 3: CONFIGURATION OF THE FIRST SETUP	7
FIGURE 4: ACCELERATIONS FIRST SETUP	7
FIGURE 5: SRS FIRST SETUP	8
FIGURE 6: SECOND SET UP	8
FIGURE 7: EXPLOSIVE SECOND SETUP.....	9
FIGURE 8: CONFIGURATION OF THE SECOND SETUP.....	9
FIGURE 9: ACCELERATIONS SECOND SETUP.....	10
FIGURE 10: SRS SECOND SETUP	10
FIGURE 11: LAGRANGE SOLVER	12
FIGURE 12: EULER SOLVER	12
FIGURE 13: FIRST MODELING	14
FIGURE 14: WEDGE FOR 50 G TNT	15
FIGURE 15: WEDGE FOR 100 G TNT	16
FIGURE 16: POSITION OF THE EXPLOSIVE	17
FIGURE 17: FLOW OUT (BOUNDARY CONDITION)	17
FIGURE 18: GAUGES IN THE PLATE.....	18
FIGURE 19: GAUGES IN THE AIR	18
FIGURE 20: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.....	19
FIGURE 21: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	20
FIGURE 22: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.....	21
FIGURE 23: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	22
FIGURE 24: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18....	23
FIGURE 25: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	24
FIGURE 26: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.....	25
FIGURE 27: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	26
FIGURE 28: REPRESENTATION OF THE PRESSURE.....	28
FIGURE 29: ZONE WHERE THE PRESSURE IS APPLIED	29
FIGURE 30: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.....	30
FIGURE 31: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	31
FIGURE 32: BEHAVIOR OF THE PLATE	31
FIGURE 33: ZONE WHERE THE PRESSURE IS APPLIED	32
FIGURE 34: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.....	33
FIGURE 36: BEHAVIOR OF THE PLATE	34
FIGURE 35: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	34
FIGURE 37: ZONE WHERE THE AREA IS APPLIED.....	35
FIGURE 38: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.....	36
FIGURE 39: DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	37
FIGURE 40: BEHAVIOR OF THE PLATE	37

FIGURE 41: POSITIONS OF THE GAUGES	38
FIGURE 42: PRESSURE DISTRIBUTION	39
FIGURE 43: PROBES ON THE PLATE.....	40
FIGURE 44: POSITIVE PHASE DURATION DISTRIBUTION	41
FIGURE 46: PROFILE OF ACCELERATIONS.....	42
FIGURE 47: PROFILE OF ACCELERATIONS.....	43
FIGURE 48: SRS FOR 0.02 KG	44
FIGURE 49: IMPULSE DISTRIBUTION	45
FIGURE 50: PROFILE OF ACCELERATIONS.....	46
FIGURE 51: SRS FOR 0.02 KG	47
FIGURE 52: SRS FOR DIFFERENT DURATIONS	48
FIGURE 53: PRESSURE DISTRIBUTION FOR 0.01 KG	49
FIGURE 54: PROFILE OF ACCELERATIONS.....	50
FIGURE 55: PRESSURE DISTRIBUTION FOR 0.03 KG	50
FIGURE 56: PROFILE OF ACCELERATIONS.....	51
FIGURE 57: PRESSURE DISTRIBUTION FOR 0.04 KG	52
FIGURE 58: PROFILE OF ACCELERATIONS.....	53
FIGURE 59: SRS FOR 10G, 20G, 30G AND 40G	53
FIGURE 60: PRESSURE DISTRIBUTION FOR 0.01 KG	54
FIGURE 61: PROFILE OF ACCELERATIONS.....	55
FIGURE 62: PRESSURE DISTRIBUTION FOR 0.03 KG	56
FIGURE 63: PROFILE OF ACCELERATIONS.....	57
FIGURE 64: PRESSURE DISTRIBUTION FOR 0.04 KG	58
FIGURE 65: VALUE OF THE ACCELERATIONS.....	58
FIGURE 66: PROFILE OF ACCELERATIONS.....	59
FIGURE 67: SRS FOR 0.01 KG, 0.02 KG, 0.03 KG AND 0.04 KG	59
FIGURE 68: GEOMETRY OF THE PROBLEM.....	60
FIGURE 69: POSITION OF THE ACCELERATIONS	61
FIGURE 70: ZONE WHERE THE PRESSURE IS APPLIED	61
FIGURE 71: PRESSURE APPLIED.....	62
FIGURE 72: ACCELERATION PROBE 1	62
FIGURE 73: ACCELERATION PROBE 2	63
FIGURE 74: DEFORMATION OF THE PLATE DUE TO THE PRESSURE	63
FIGURE 75: AREA WHERE THE PRESSURE IS APPLIED	64
FIGURE 76: SINUSOIDAL PRESSURE	64
FIGURE 77: ACCELERATION PROBE 1	65
FIGURE 78: ACCELERATION PROBE 2	65
FIGURE 79: DEFORMATION OF THE PLATE	65
FIGURE 80: POSITION OF THE GAUGES.....	66
FIGURE 81: PRESSURE DISTRIBUTION	67
FIGURE 82: MODELISATION OF THE PRESSURE DISTRIBUTION	68
FIGURE 83: PRESSURE PROFILE	68
FIGURE 84: GAUGES	69
FIGURE 85: ACCELERATION IN Z-AXE OF THE PLATE.....	70
FIGURE 86 FORMATION OF A DISCONTINUITY FRONT	75

FIGURE 87: PRESSURE DEPENDING ON THE DISTANCE TO THE CENTER OF THE EXPLOSION 75

FIGURE 88: REPRESENTATION OF THE SHOCK WAVE 76

9 INDEX OF TABLES

TABLE 1: ADVANTAGES AND DISADVANTAGES OF LAGRANGE SOLVER.....	12
TABLE 2: ADVANTAGES AND DISADVANTAGES OF EULER SOLVER.....	12
TABLE 3: POSITION OF THE SPHERES	16
TABLE 4: POSITIONS FOR THE ACCELEROMETERS	17
TABLE 5: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.	19
TABLE 6: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	20
TABLE 7: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.	21
TABLE 8: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	22
TABLE 9: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.	23
TABLE 10: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	24
TABLE 11: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 8, 13 AND 18.	25
TABLE 12: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	26
TABLE 13: SUMMARY OF THE DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 26 AND 27.....	27
TABLE 14: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.	29
TABLE 15: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	30
TABLE 16: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.	32
TABLE 17: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	33
TABLE 18: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 3, 8, 13, 18 AND 23.	35
TABLE 19: MAXIMUM VALUES OF DISPLACEMENTS, VELOCITIES AND ACCELERATIONS OF GAUGES 26 AND 27.....	36
TABLE 20: POSITIONS OF THE GAUGES	38
TABLE 21: EQUIVALENCE BETWEEN THE NUMERICAL AND EXPERIMENTAL NUMERATION.....	38
TABLE 22: PRESSURE DISTRIBUTION	39
TABLE 23: GAUGES AND ZONES	40
TABLE 24: DIAMETER, PRESSURE APPLIED, POSITIVE PHASE DURATION FOR EACH ZONE	41
TABLE 25: VALUE OF THE ACCELERATIONS	42
TABLE 26: POSITIVE PHASE DURATION FOR EACH ZONE.....	43
TABLE 27: VALUE OF THE ACCELERATIONS	43
TABLE 28: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE	45

TABLE 29: VALUE OF THE ACCELERATIONS	46
TABLE 30: COMPARISON OF THE ACCELERATIONS FOR 20G	47
TABLE 31: CORRESPONDENCE BETWEEN THE EXPERIMENTAL AND NUMERICAL NUMERATION	47
TABLE 32: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.01 KG)	49
TABLE 33: VALUE OF THE ACCELERATIONS	49
TABLE 34: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG)	51
TABLE 35: VALUE OF THE ACCELERATIONS	51
TABLE 36: DIAMETER, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.04 KG)	52
TABLE 37: VALUE OF THE ACCELERATIONS	52
TABLE 38: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.01 KG) ..	54
TABLE 39: VALUE OF THE ACCELERATIONS	55
TABLE 40: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG) ..	56
TABLE 41: VALUE OF THE ACCELERATIONS	57
TABLE 42: IMPULSE, PRESSURE AND POSITIVE PHASE DURATION FOR EACH ZONE (0.03 KG) ..	58
TABLE 43: MAXIMUM ACCELERATION FOR PROBE 1 AND PROBE 2.....	62
TABLE 44: MAXIMUM ACCELERATION FOR PROBE 1 AND PROBE 2.....	64
TABLE 45: POSITION OF THE GAUGES	66
TABLE 46: EQUIVALENCE BETWEEN THE NUMERICAL AND EXPERIMENTAL NUMERATION.....	66
TABLE 47: ZONES, DIAMETERS AND PRESSURES APPLIED	67
TABLE 48: SIGNAL PRESSURE APPLIED	68
TABLE 49: ACCELERATION OF THE GAUGES	70
TABLE 50: TNT EQUIVALENTS.....	74